LOAN DOCUMENT

PHOTOGRAPH THIS SHEET

DTIC ACCESSION NUMBER

LEVEL

0

INVENTORY

WL-TR-97-4077

DOCUMENT IDENTIFICATION

APR 97

DISTRIBUTION STATEMENT A

Approved for public release;
Distribution Unlimited

DISTRIBUTION STATEMENT

HANDLE WITH CARE

ACCESSION FOR

NTIS GRA&I ☒
DTIC TRAC ☐
UNANNOUNCED ☐
JUSTIFICATION

BY

DISTRIBUTION/

AVAILABILITY CODES

DISTRIBUTION	AVAILABILITY AND/OR SPECIAL	
A-1		

DISTRIBUTION STAMP

DATE ACCESSIONED

DTIC QUALITY INSPECTED 3

DATE RETURNED

19970711 017

DATE RECEIVED IN DTIC

REGISTERED OR CERTIFIED NUMBER

PHOTOGRAPH THIS SHEET AND RETURN TO DTIC-FDAC

DTIC FORM JUN 90 70A

DOCUMENT PROCESSING SHEET

PREVIOUS EDITIONS MAY BE USED UNTIL STOCK IS EXHAUSTED.

LOAN DOCUMENT

WL-TR-97-4077

PROCEEDINGS OF THE ANNUAL MECHANICS OF COMPOSITES REVIEW (14TH)

Sponsored by:

Air Force Wright Aeronautical Laboratories
Materials Laboratory

APRIL 1997

FINAL REPORT FOR PERIOD 31 OCTOBER 1989 - 1 NOVEMBER 1989

Approved for public release; distribution unlimited

MATERIALS DIRECTORATE
WRIGHT LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AFB OH 45433-7734

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 1997	Final Report 31 Oct 89 - 1 Nov 89

4. TITLE AND SUBTITLE

PROCEEDINGS OF THE ANNUAL MECHANICS OF COMPOSITES REVIEW (14th)

5. FUNDING NUMBERS

6. AUTHOR(S)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Materials Laboratory
Nonmetallic Materials Division
Wright-Patterson AFB OH 45433

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Materials Directorate
Wright Laboratory
Air Force Materiel Command
Wright-Patterson AFB Ohio 45433-7734
POC:Tammy Oaks, WL/MLBM, 937-255-3068

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

WL-TR-97-4077

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION AVAILABILITY STATEMENT

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report contains the basic unedited vu-graphs of the presentations at the "Mechanics" of Composites Review" sponsored jointly by the Non-metallic Materials Division of the Air Force Materials Laboratory, the Structures Division of the Air Force Flight Dynamics Laboratory and the Directorate of Aerospace Sciences of the Air Force Office of Scientific Research. The presentations cover current in-house and contract programs under the sponsorship of these three organizations.

14. SUBJECT TERMS

epoxy-matrix composites; composite materials; resin matrix composites; composite bonded joints; fatigue of graphite/epoxy composites; fracture and fatigue of bi-materials

15. NUMBER OF PAGES

172

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

AGENDA
MECHANICS OF COMPOSITES REVIEW
31 OCTOBER AND 1 NOVEMBER 1989

TUESDAY, 31 OCTOBER 1989

WEDNESDAY, 1 NOVEMBER 1989 PAGE

*NAAP - NOT AVAILABLE AT PRINTING

FOREWORD

This report contains the abstracts and viewgraphs of the presentations at the Fourteenth Annual Mechanics of Composites Review sponsored by the Materials Laboratory. Each was prepared by its presenter and is published here unedited. In addition, a listing of both the in-house and contractual activities of each participating organization is included.

The Mechanics of Composites Review is designed to present programs covering activities throughout the United States Air Force, Navy, NASA, and Army. Programs not covered in the present review are candidates for presentation at future Mechanics of Composites Reviews. The presentations cover both in-house and contractual programs under the sponsorship of the participating organizations.

Since this is a review of on-going programs, much of the information in this report has not been published as yet and is subject to change; but timely dissemination of the rapidly expanding technology of advanced composites is deemed highly desirable. Works in the area of Mechanics of Composites have long been typified by disciplined approaches. It is hoped that such a high standard of rigor is reflected in the majority, if not all, of the presentations in this report.

Feedback and open critique of the presentations and the review itself are most welcome as suggestions and recommendations from all participants will be considered in the planning of future reviews.

Deborah Perdue

DEBORAH PERDUE, Meeting Manager
Mechanics & Surface Interactions Branch
Nonmetallic Materials Division
Materials Laboratory

ACKNOWLEDGEMENT

We wish to express our appreciation to the authors for their contributions; to the focal points within the organizations for their efforts in supplying the program listings; and to Lisa Wilson and Barbara Woolsey for managing registration.

MATRIX CRACK INITIATION IN CERAMIC MATRIX COMPOSITES

A. S. D. Wang
Department of Mechanical Engineering and Mechanics
and
M. W. Barsoum
Department of Materials Engineering

Drexel University
Philadelphia, PA 19104

ABSTRACT

One of the limitations of fiber-reinforced ceramic matrix composites is the low tensile strains at which the matrix cracks. This subcritical failure mode signifies the onset of permanent damage in the composite at an early loading stage; and its accumulation can result in the loss of protection provided by the matrix against oxidation or corrosion of the fibers. Efforts to increase the threshold strain of matrix cracking have centered around the issues of the fiber-matrix interface bonding. However, this has led to some dilemma and controversy.

On one hand, strong interface bonding is desirable because it suppresses matrix cracking likelihood, thus increasing the matrix cracking strain. Strong interface bonding, however, is suspect of precipitating brittle and catastrophic composite failure due to fiber fracture in the wake of a major matrix crack propagation. On the other hand, weak interface bonding lowers the threshold strain of matrix cracking, but it allows the fibers to remain intact thus providing a larger apparent strain to failure for the composite.

The controversy, then, is centered around the question whether there is an "optimal" interface bonding which provides sufficient fiber-matrix load-transfer to elevate the matrix cracking threshold strain, while still retain the apparent composite strength and toughness controlled by the intact reinforcing fibers.

This question raises several research issues related to mechanics. One of the issues is the mechanics representation and quantification of interface bonding. Another is the mechanics relations linking interface bonding, matrix cracking mechanisms and the composite's subcritical failure processes.

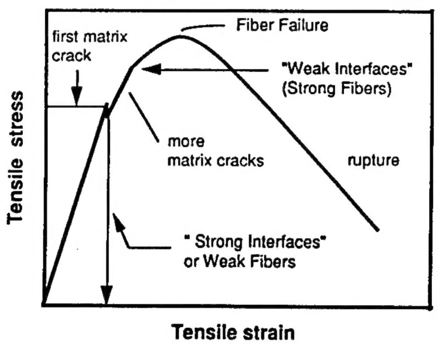
During the past year, a rational research approach has been initiated in which the mechanics issues of interface and matrix cracking in ceramic matrix composites are examined by controlling the composite's microstructure and micromechanics variables in a closed-loop framework involving fabrication, testing, modeling and simulations.

In this presentation, major developments in specimen fabrication, matrix crack test methods and crack detection techniques, modeling concepts and simulation procedures are discussed. An important, while still preliminary, comparison between the simulated results and the experiment is presented; future works are outlined.

PROBLEM STATEMENT

DILEMMA AND CONTROVERSY:

- **Strong interface bonding limits matrix cracks, but precipitates a brittle failure mode,.....low apparent toughness;**
- **Weak interface bonding lowers matrix crack threshold, but allows a graceful (ductile) failure mode,.......greater toughness;**
- **"Optimal" interface bonding promotes efficient fiber-matrix load-transfer, suppresses matrix crack threshold, provides a greater apparent composite toughness ?**



RESEARCH ISSUES:

- **Mechanics representation & quantification of interface bonding;**
- **Mechanics relations linking interface bonding, matrix cracking and apprent composite toughness.**

PROGRAM OBJECTIVES

* Develop Simulation Models that

- account for the fundamental parameters influencing matrix crack mechanisms in ceramic matrix composites

- determine matrix crack initiation and simulate matrix cracking evolution

* Develop Experimental Capability to

- fabricate test specimens with controlled microstructural and processing variables

- test specimens under varying surface preparation, different loading conditions and high temperature environments

- measure matrix cracking initiation stress and crack evolution in real-time

* Conduct Experimental, Theoretical and Numerical Simulation Correlations.

APPROACH OVERVIEW

⇓

FABRICATION

- **material selection**
  - **mismatch in stiffness**
  - **mismatch in thermal property**
- **interface control**
- **fiber spacing, fiber diameter variation**

⇓

SPECIMEN PREPARATION

- **control of surface finish**
  - **effect of etching**
  - **effect of scratching & polishing**

⇓

DATA BASE COMPILATION

- **matrix fracture toughness (K_c) in temperature**
- **interface bonding (τ) in temperature**

⇓

TESTING

- **loading conditions**
  - **3- & 4-point bend**
  - **uniaxial tension**
- **determine MCS**
- **record crack evolution**
- **subscale SEM study**

⇓

MODELS & SIMULATIONS

- **flaw-crak interaction**
  - **fracture mechanics**
  - **determines MCS**
- **Monte-Carlo simulation**
  - **crack evolution**

⇓

CORRELATION & FEEDBACK

- **behavior of major factors**
  - **range of influence**
- **validation of models**
- **predict behavior of new material, microstructure, etc**

RESULTS

- Material Selection & Fabrication-

- **SiC/LAS# (Nicalon), 50 v%**
- **SiC/Borosilicate (AVCO), 17 v%**
- **C/Borosilicate, 40 V%, 45 v%**

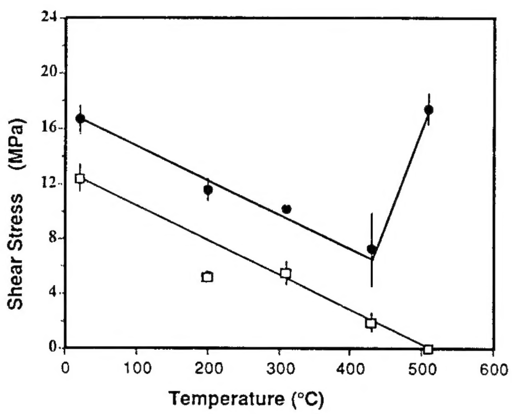
Appropriate Constituents Properties:

	SiC/LAS	SiC/Borosilicate	C/Borosilicate
E_f	200 GPa	400 GPa	380 GPa
E_m	85 GPa	63 GPa	63 GPa
ν_f	0.3	0.3	0.3
ν_m	0.3	0.3	0.3
α_f	$3\times10^{-6}/^oC$	$2.6\times10^{-6}/^oC$	$0.1\times10^{-6}/^oC$
α_m	$4\times10^{-6}/^oC$	$3.2\times10^{-6}/^oC$	$3.2\times10^{-6}/^oC$
R	8 μm	70 μm	4 μm
Kc^m	2 MPa√m	0.75 MPa√m	0.75 MPa√m
τ^+	2 MPa	10 MPa	10-25 MPa
ΔT	1200 ^oC	490 ^oC	490 ^oC

 # data taken from Marshall, Cox and Evans (1985)
+ as reported in literature

DATA BASE COMPILATION

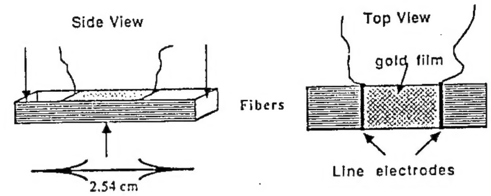
* Interface shear strength (τ) in temperature
* by single fiber (AVCO SiC) pull-out test
* Soda-lime used as matrix material

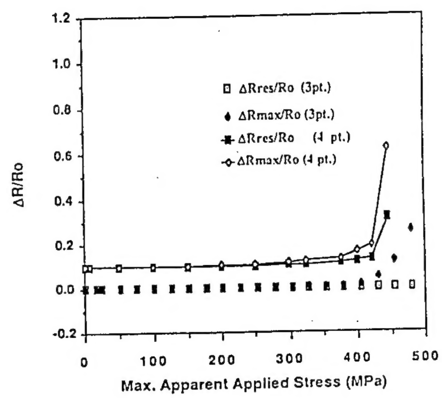


Temperature dependence of debonding (filled circle) and frictional (open square) shear stresses for a single SiC fiber embedded in a soda-lime glass matrix. Upturn at 500 °C in debond stress is most probably due to fiber oxidation.

TESTING & INSTRUMENTATION

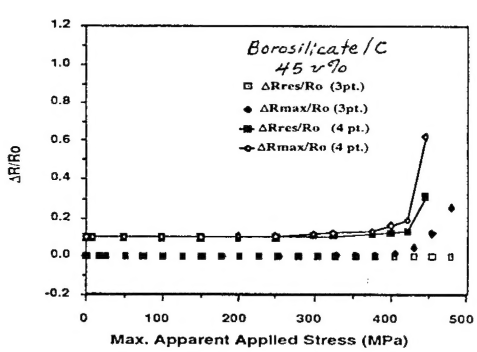
- 3 & 4 point bend & gold-film technique -

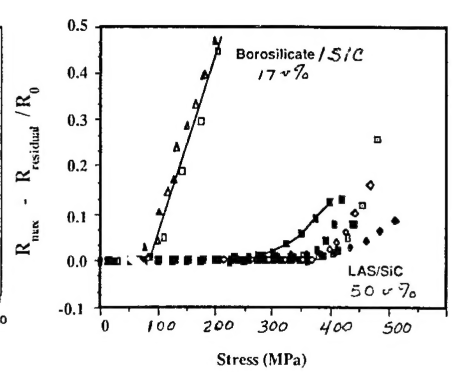




TEST RESULTS

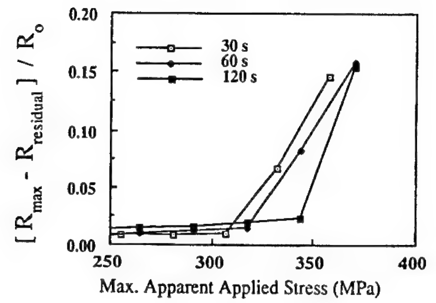
- 3 & 4 point bend tests give same results
- MCS data scatter less than ±10%
- all tests conducted in ambient temperature



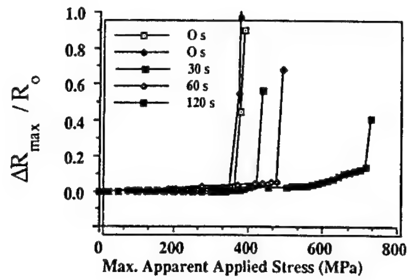


EFFECT OF ETCHING

submerge specimen in 5% HF solution to remove small surface flaws



Effect of etching (5% HF) for times indicated on MCS of a 50 v%SiC fibers in a lithium-alumino silicate matrix

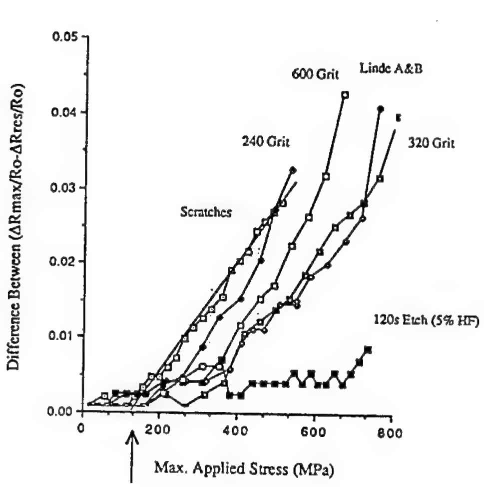


Effect of etching (5% HF) for times indicated on MCS of a 45 v% C fibers in borosilicate (CGW 7740) matrix

EFFECT OF SURFACE SCRATCHING

- to introduce surface flaws normal to stress -

Specimens: C/Borosilicate, 40 v%

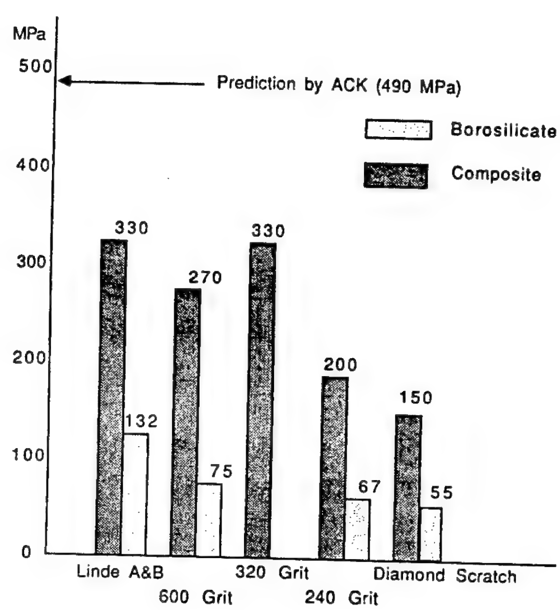


EFFECT OF SURFACE SCRATCHING

- to introduce surface flaws normal to stress -

Specimens: Monolithic Borosilicate & C/Borosilicate, 40 v%

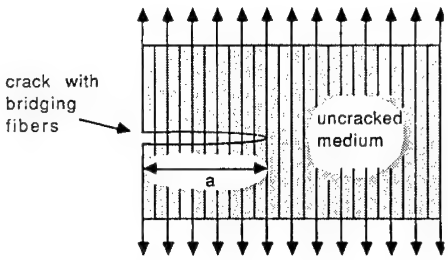
Major results: Effective flaw size, a ≈ d



MATRIX CRACKING MODELS

Long-crack Models:

* Aveston, Cooper and Kelly (1971)
* Budiansky, Hutchinson and Evans (1986)



First matrix cracking strain by ACK:

$$(e_m)_{cr} = \{[12\,\gamma_m\,\tau\,E_f\,(V_f)^2]/[E_c\,E_m^2\,V_m\,R]\}^{1/3}$$

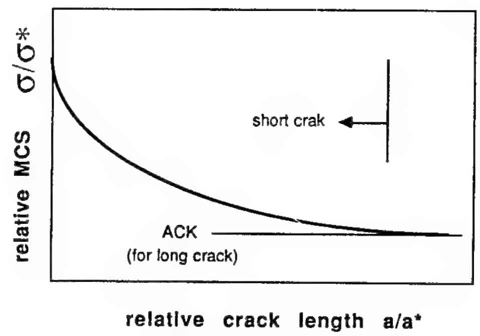
requiring 2 material failure quantities:

crack surface energy of matrix, γ_m
interface debonding/sliding strength, τ

MATRIX CRACKING MDELS

Short-crack Models (extension of ACK):

* Marshall, Cox and Evans (1985)
* McCartney (1987)



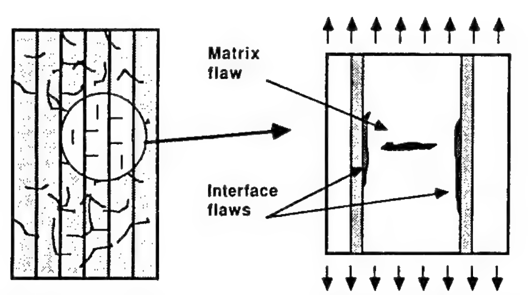
a* is an arbitrary length constant dependending on γ_m and τ (and other non-failure quantities);

σ^* is an arbitrary stress constant dependending on γ_m and τ (and other non-failure quantities).

The MCS curve is a universal relation.

FLAW - INTERACTION MODEL

- intrinsic flaws, idealized flaws & their local interactions -

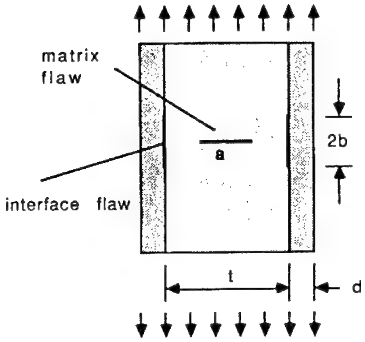


Unidirectional composite with manufacturing flaws

Idealized local flaws and interaction configuration

Chain of interaction: local interface disbonds→matrix cracks→crack linking→loss of composite toughness

FLAW INTERACTION MODEL UNIT-CELL



Matrix crack driving force:

$$G(e_c, \Delta T) = [\sqrt{C_e(a,b)}\,(e_c) + \sqrt{C_T(a,b)}\,\Delta T]^2\, d$$

Matrix cracking criterion:

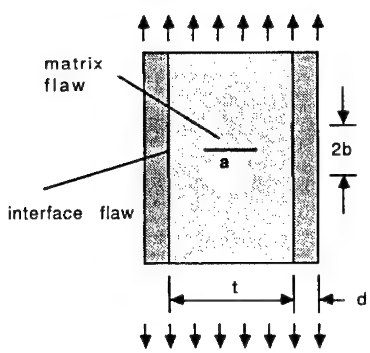
$$G(e_c, \Delta T) = G_m$$

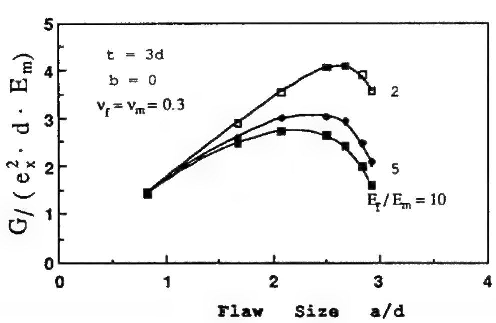
The flaw sizes a & b are random material variables.

The location of the unit-cell is also randomly distributional.

Assuming perfect bonding,or no interface flaw exists (b=0),....

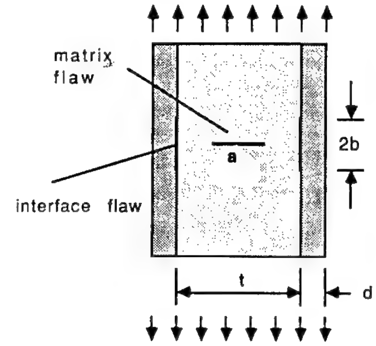
· effect of fiber/matrix stiffness on strain energy release rate:

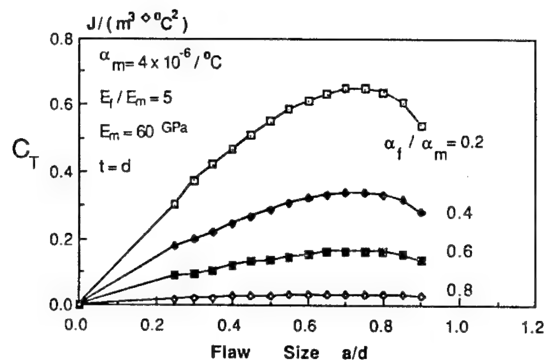




Effect of fiber/matrix thermal expansion mismatch on strain energy release rate:

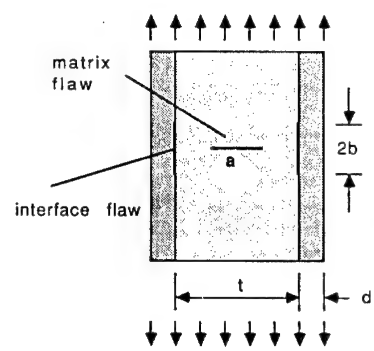
$$G(e_c, \Delta T) = [\sqrt{C_e(a,b)}\,(e_c) + \sqrt{C_T(a,b)}\,\Delta T]^2\, d$$

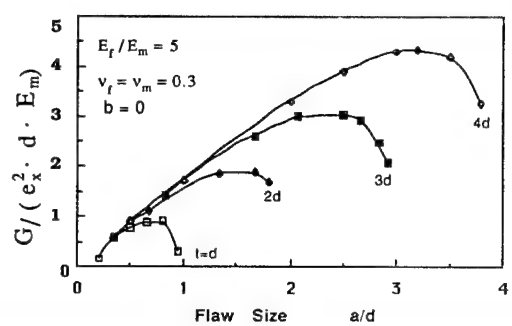




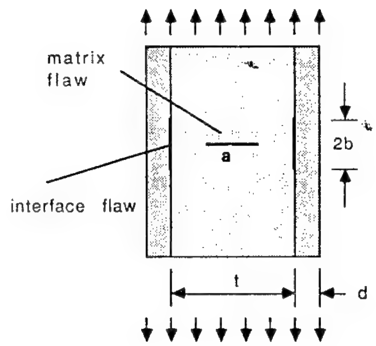
Assuming perfect bonding, or no interface flaw exists (b = 0), . . .

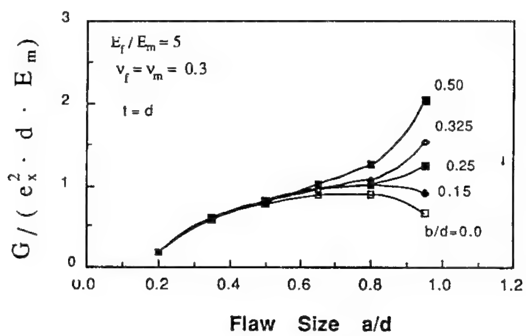
*** effect of fiber spacing, ...**





Assuming variable bonding,or at the worst interface flaw site (b>0),....





SUMMARY OF RESULTS

- comparison of experiment & predictions -

Specimens	Experiment	ACK Model	Flaw-Interaction
SiC/LAS 50 v%	370±10 MPa	265 MPa	377 MPa (b≈d)
SiC/ Borosilicate 17 v%	78±10 MPa	71.5 MPa	73 MPa (b=0)
C/Borosilicate 40 v%	330±20 MPa	490 MPa	340 MPa (b=0)
C/Borosilicate 45 v%	360±2 MPa	584 MPa	361 MPa (b=0)

* all specimens polished with Linde A & B before test.

* minimum reported τ used in ACK Model for C/borosilicates

* effective matrix flaw size a ≈ 0.85d used in the Flaw-Interaction Model

CONCLUSIONS

* Rational frame to study damage mechanics in ceramic matrix composites established

* Specimen fabrication to control important micromechanics variables initiated

* Preliminary experiments support the Flaw-Interaction Modeling concept

FUTURE WORK

* Continued experiment-simulation correlation needed for further understanding

* Modeling of damage evolution to evaluate material reliability & durability characteristics

* Expansion of baseline data bank needed for high temperature studies.

FAILURE MECHANISMS IN CERAMIC-MATRIX COMPOSITES

I. M. Daniel, G. Anastassopoulos and J.-W. Lee

The Technological Institute
Northwestern University
Evanston, IL 60208

ABSTRACT

Ceramic matrix composites behave nonlinearly and inelastically beyond a relatively low stress threshold. Their overall behavior under load is intimately related to the micromechanisms of inelastic deformation and failure that develop and interact with each other. Composites consisting of glass-ceramic matrices, such as lithium aluminosilicate (LAS) and calcium aluminosilicate (CAS), reinforced with silicon carbide yarn or monofilament have been developed. Failure mechanisms in a SiC/LAS composite under longitudinal tensile loading have been observed and discussed by Marshall and Evans [1]. Although the various failure mechanisms in such cases are known, their relative magnitude, exact sequence and quantitative effect on overall behavior are not fully understood. Of great importance is the influence of constituent properties, including fiber, matrix and interphase region, on the failure process and overall behavior. This study deals with failure mechanisms in a SiC/CAS unidirectional composite under transverse and longitudinal tensile loading [2]. Failure mechanisms were studied by testing unidirectional specimens under the microscope with a specially designed fixture.

Under longitudinal loading for fully bonded fibers, the axial strain is the same in both fiber and matrix. As the load increases, the phase with the lower ultimate strain, in this case the matrix, will fail by transverse cracking. In the vicinity of a matrix crack the axial stress in the matrix is relieved while the axial fiber stress is increased and a highly localized interfacial shear stress develops. Matrix cracking increases in density until the crack spacing is short enough that the maximum axial stress in the matrix is below its tensile strength. This limiting crack density is a function of material and geometric parameters of the specimen. At some point other failure mechanisms develop and interact. For example, the high interfacial shear stress would cause at least local fiber debonding with the maximum fiber stress causing fiber fractures. The initial failure consists of transverse matrix cracks increasing in density with applied stress up to a limiting level of approximately 28 cracks/mm or a minimum crack spacing of 36 μm (0.014 in.), which corresponds approximately to two fiber diameters. Isolated fiber breaks were observed before matrix crack saturation. At a stress level well below the ultimate, no further matrix or fiber failures occur, and the material behaves linearly. It is believed that at some point before ultimate failure there is complete fiber/matrix debonding. In this last stage of deformation the material behaves linearly as if it consisted only of a bundle of fibers.

Under transverse tensile loading initial failure takes the form of radial cracks in the matrix starting at the fiber/matrix interface. In relatively isolated fibers this cracking occurs at the 90° location from the loading axis. In more closely near hexagonally packed fibers, crack initiation occurs at approximately 45° from the loading axis. These phenomena can be explained by micromechanical analyses assuming a low stiffness thin interphase region between the fiber and the matrix. Subsequently, interfacial cracks are developed which are eventually connected with the radial cracks to form a continuous catastrophic crack.

REFERENCES

1. Marshall, D. B. and Evans, A. G., "Failure Mechanisms in Ceramic-Fiber/Ceramic-Matrix Composites," Journal of the Amer. Ceramic Soc., vol. 68, May 1985, pp. 225-231.

2. Daniel, I. M., Anastassopoulos, G. and Lee, J.-W., "Failure Mechanisms in Ceramic Matrix Composites," Proc. 1989 SEM Spring Conf. on Experimental Mechanics, May 29 - June 1, 1989, Cambridge, MA, pp. 832-838.

FAILURE MECHANISMS IN CERAMIC MATRIX COMPOSITES

BY

I. M. DANIEL
G. J. ANASTASSOPOULOS
J.-W. LEE

NORTHWESTERN UNIVERSITY
EVANSTON, IL 60208

OBJECTIVE

Study failure mechanisms on a microscopic scale in a unidirectional ceramic matrix composite under longitudinal and transverse tensile loading.

SCOPE

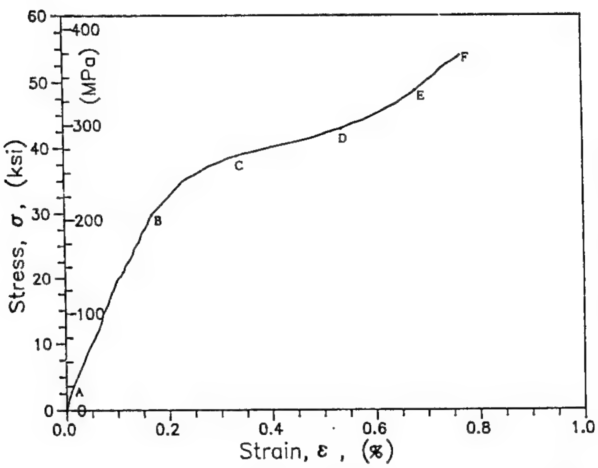
Material:	SiC/CAS (Silicon carbide/calcium aluminosilicate)	
Specimens:	Unidirectional	0-deg
	Unidirectional	90-deg
	Crossply	$[0/90]_{2s}$
Experiments:	Macroscopic characterization	
	Microscopic observations	
	Correlation of microscopic and macroscopic behavior	

Table 1. Constituent Material Properties

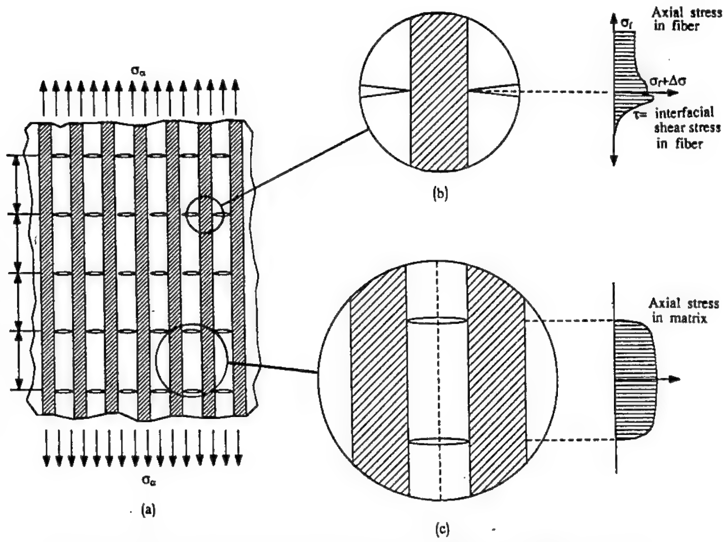
Property	CAS Matrix [3]	SiC Fiber [1,2]
Maximum Use Temperature, °C (°F)	1350 (2460)	1300 (2370)
Fiber Diameter (μm)	-	15
Density (g/cm^3	2.8	2.6
Coefficient of Thermal Expansion, 10^{-6}/°C(10^{-6}/°F)	5.0 (2.8)	3.1 (1.7)
Elastic Modulus, GPa (10^6 psi)	98 (14.2)	207-234(30-34)
Tensile Strength, MPa (ksi)	124 (18) (flexural)	2060 (300)

Table 2. Measured Properties of SiC/CAS Unidirectional Composite

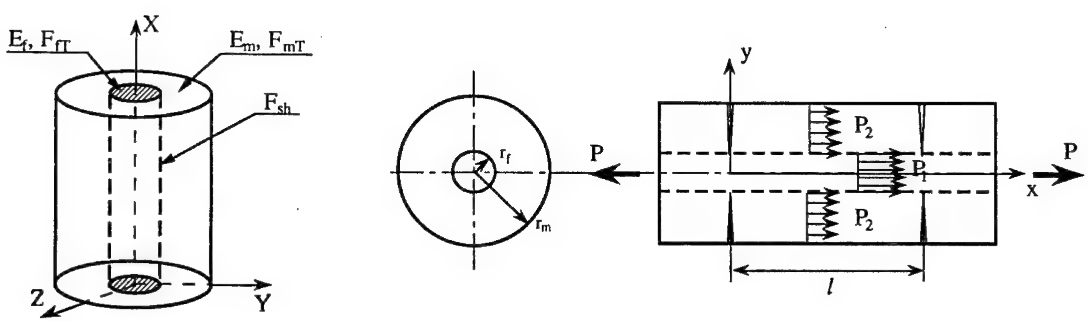
Property	Value
Fiber Volume Ratio, V_f	0.39
Ply Thickness, t, mm (in.)	0.38 (0.015)
Longitudinal Modulus, E_1, GPa (Msi)	121 (17.6)
Transverse Modulus, E_2, GPa (Msi)	112 (16.2)
In-plane Shear Modulus, G_{12}, GPa (Msi)	52 (7.5)
Major Poisson's Ratio, ν_{12}	0.30
Longitudinal Tensile Strength, F_{1T}, MPa (ksi)	393 (57)
Transverse Tensile Strength, F_{2T}, MPa (ksi)	22 (3.2)
Longitudinal Ultimate Tensile Strain, ϵ^u_{1T}	0.0084
Transverse Ultimate Tensile Strain, ϵ^u_{2T}	0.0002



Stress-Strain Curve for $[0_8]$ SiC/CAS Specimen Under Uniaxial Tensile Loading



Matrix Cracking and Local Stress Distributions in Longitudinally Loaded Specimen



Geometry and Loading in Ceramic Composite

Equilibrium $$P = P_1 + P_2 \qquad (1)$$

Assume

$$\frac{dP_2}{dx} = H\,(u_2 - u_1)$$

or $$\frac{d^2P_2}{dx^2} = H\,(\bar{\varepsilon}_2 - \bar{\varepsilon}_1) \qquad (2)$$

Where H = Constant

$$\bar{\varepsilon}_1 = \frac{P_1}{\pi\, r_f^2\, E_f} = \frac{P - P_2}{\pi V_f\, r_m^2\, E_f}$$

$$\bar{\varepsilon}_2 = \frac{P_2}{\pi V_m\, r_m^2\, E_m}$$

Governing Equation $$\frac{d_2P_2}{dx^2} - \alpha^2 P_2 = -\beta \qquad (3)$$

Where

$$\alpha^2 = \frac{H}{\pi\, r_m^2}\left(\frac{1}{E_f V_f} + \frac{1}{E_m V_m}\right)$$

$$\beta = \frac{H}{\pi\, r_m^2}\frac{P}{E_f V_f}$$

General Solution

$$P_2 = \frac{\beta}{\alpha^2} + R\sinh(\alpha x) + S\cosh(\alpha x)$$

Boundary Conditions

(a) $P_2 = 0$ at $x = 0$ and $x = l$

(b) $\tau_{xr} = 0$ at $r = 0$ and $r = r_m$

(c) $\tau_{xr} = \tau_i$ at $r = r_f$

(d) $u_1 = u_2$ at $r = r_f$

From B.C. (a)

$$P_2 = \frac{E_m V_m}{E_f V_f + E_m V_m}\left(1 - \frac{\cosh\left(\frac{\alpha l}{2} - \alpha x\right)}{\cosh\left(\frac{\alpha l}{2}\right)}\right)P$$

and

$$P_1 = \frac{E_f V_f}{E_f V_f + E_m V_m}\left(1 + \frac{E_m V_m}{E_f V_f}\frac{\cosh\left(\frac{\alpha l}{2} - \alpha x\right)}{\cosh\left(\frac{\alpha l}{2}\right)}\right)P$$

Determine Constant H

- **Assume Linear Shear Stress Distributions in the Fiber and Matrix to r-direction.**

$0 \le r \le r_f$ $\quad u_1 = c_1 r^2 + c_2 r + c_3$, $\quad \tau_{rx1} = G_f(2c_1 r + c_2)$

$r_f \le r \le r_m$ $\quad u_2 = c_4 r^2 + c_5 r + c_6$, $\quad \tau_{rx2} = G_m(2c_4 r + c_5)$

- **Using B.C. (b), (c), (d) and the Equlibrium Condition in the Matrix**

$$\frac{dP_2}{dx} = -2\tau_i \pi r_f$$

We get

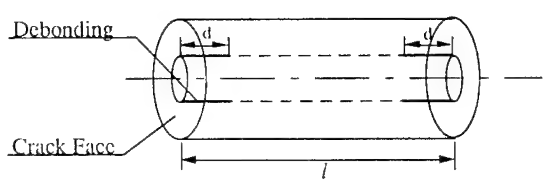
$$H = -\frac{2\pi r_f}{A}$$

where $$A = \frac{r_f}{4G_f} + \frac{1}{4G_m(r_f + r_m)V_m r_m}\left\{V_m^2 r_m^3 + 4V_m r_m^2 r_f - \frac{3}{8}(r_f^3 - r_m^3)\right\}$$

Partial Debonding Between Fiber and Matrix

- Debonding occurs if $|\tau_i| \ge F_{sh}$

$$\tau_i(x) = -\frac{\alpha P}{2\pi r_f}\frac{E_m V_m}{E_f V_f + E_m V_m}\frac{\sinh\left(\frac{\alpha l}{2} - \alpha x\right)}{\cosh\left(\frac{\alpha l}{2}\right)}$$



d : Debonded Length

l : Crack Spacing

$$d = \frac{1}{2}\left(l - \frac{2}{\alpha}\ln\left(\xi + \sqrt{\xi^2 + 1}\right)\right)$$

where $$\xi = \frac{2\pi r_f F_{sh}}{\alpha P}\frac{E_f V_f + E_m V_m}{E_m V_m}\cosh\left(\frac{\alpha l}{2}\right)$$

Average Stress in Fiber with debonding length 2d

$$\bar{\sigma}_{1f} = \frac{1}{\pi r_f^2}\left\{\frac{2d}{l} + \frac{E_f V_f}{E_f V_f + E_m V_m}\left[\frac{l - 2d}{l} + \frac{E_m V_m}{E_f V_f}\frac{\tanh\left(\frac{\alpha l}{2}\right)}{\frac{\alpha l}{2}}\right]\right\}P$$

Average Force in Fiber (in between two neighbouring cracks)

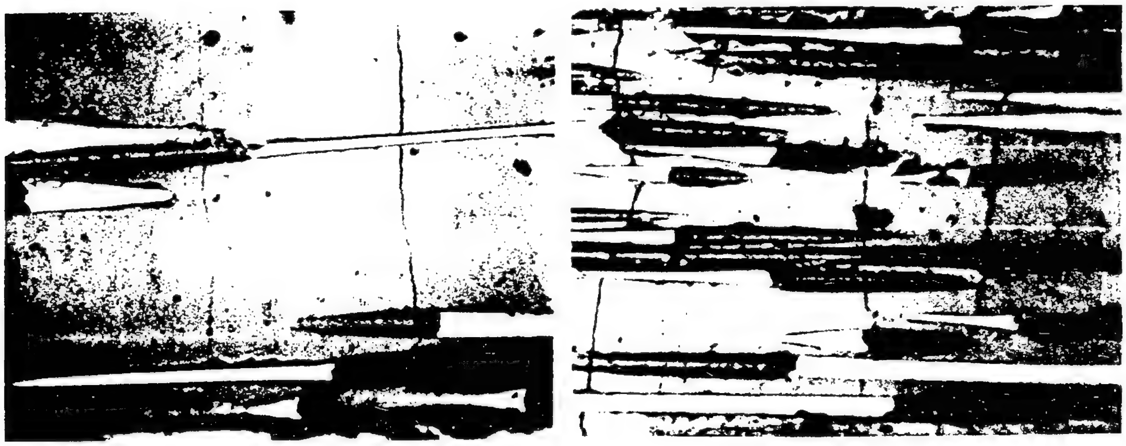
$$\bar{P}_1 = \frac{E_f V_f}{E_f V_f + E_m V_m}\left(1 + \frac{E_m V_m}{E_f V_f}\frac{\tanh\left(\frac{\alpha l}{2}\right)}{\left(\frac{\alpha l}{2}\right)}\right)P$$

Average Tensile Strain in Fiber

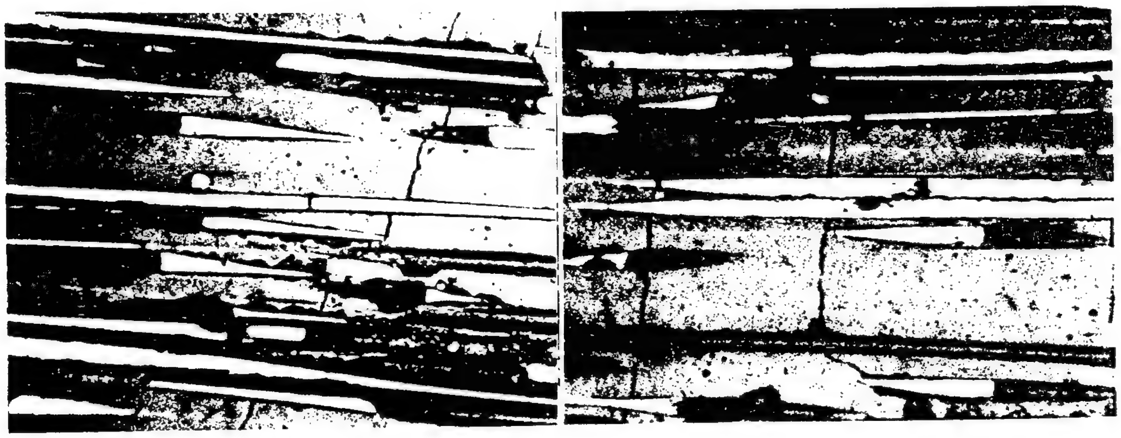
$$\bar{\varepsilon}_1 = \frac{\sigma_a}{E_o}\left(1 + \frac{E_m V_m}{E_f V_f}\frac{\tanh\left(\frac{\alpha l}{2}\right)}{\left(\frac{\alpha l}{2}\right)}\right)$$

Reduced Axial Modulus

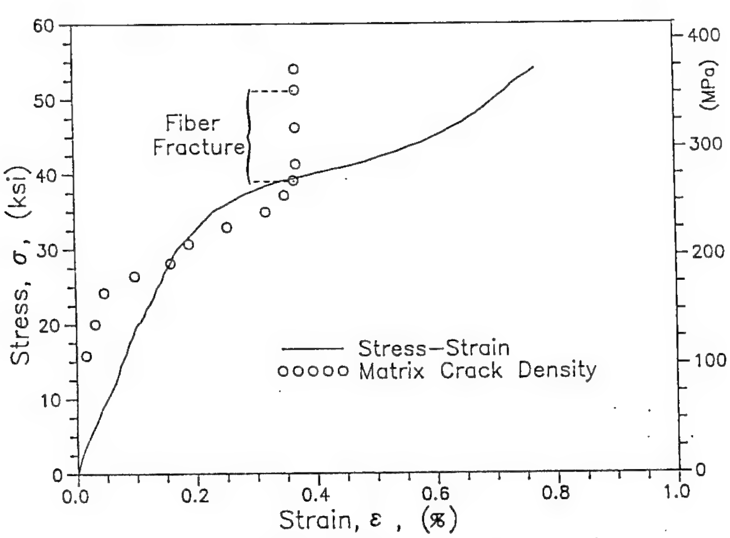
$$\frac{E_x}{E_o} = \frac{1}{\left(1 + \frac{E_m V_m}{E_f V_f}\frac{\tanh\left(\frac{\alpha l}{2}\right)}{\left(\frac{\alpha l}{2}\right)}\right)}$$



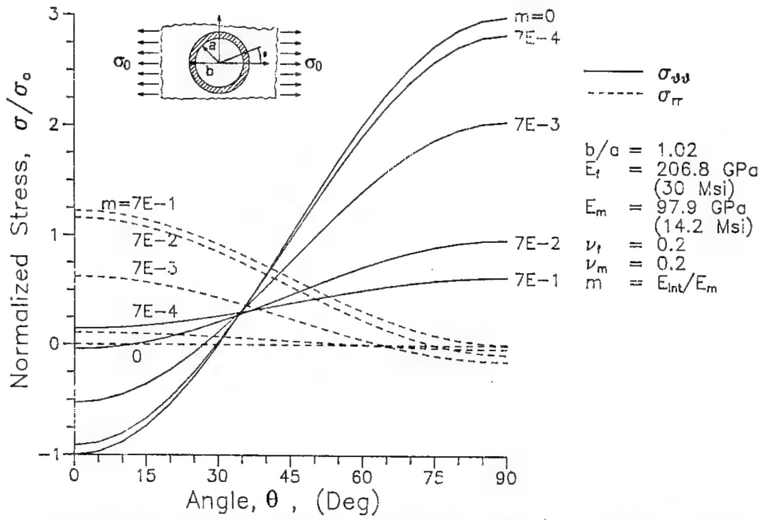
Typical Photomicrographs showing initiation and multiplication of transverse matrix cracks under longitudinal tensile loading



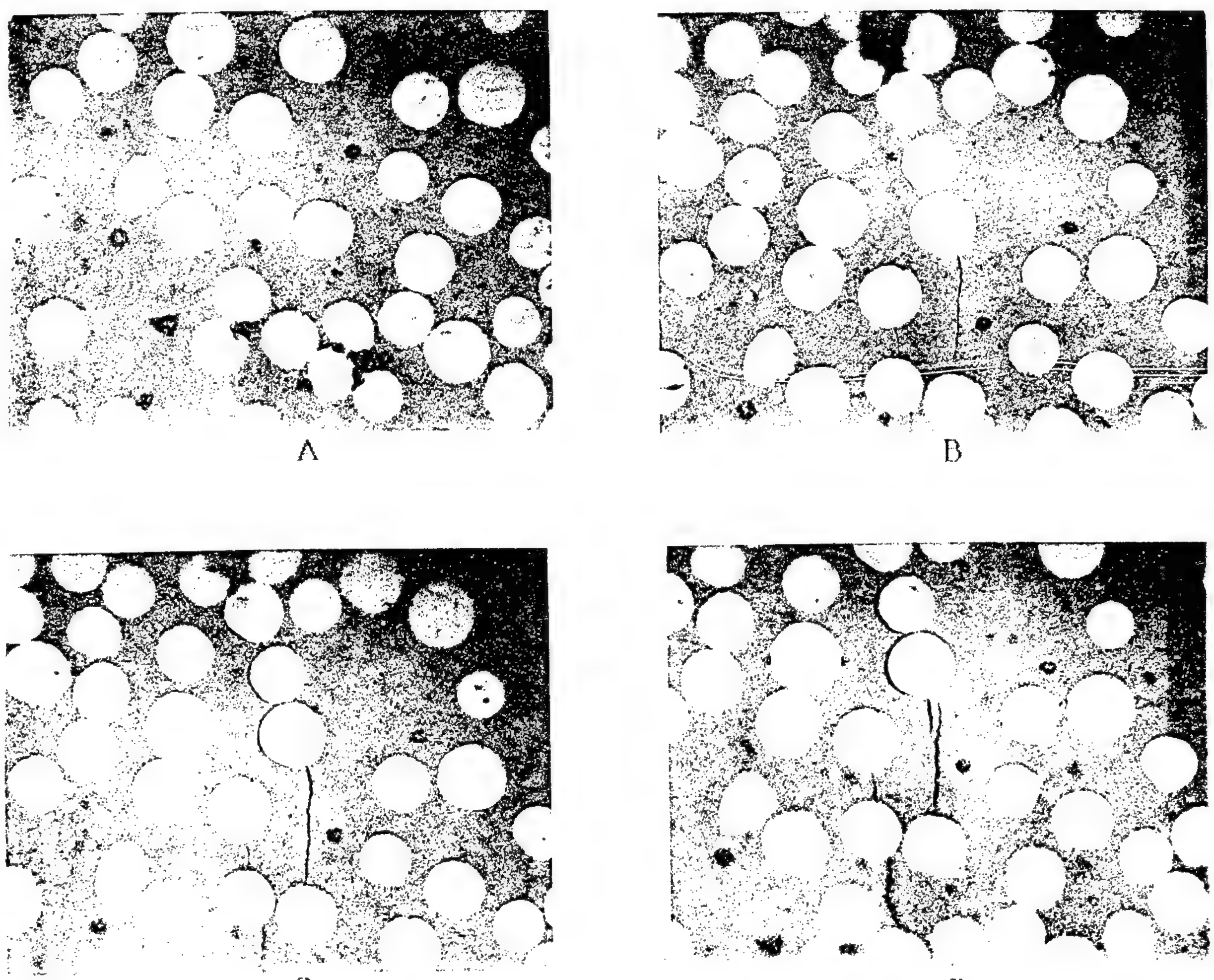
Photomicrographs illustrating fiber fractures and fiber crack opening between matrix cracks



Normalized Crack Density, λd



Stresses Around Inclusion with Interphase Liner in Infinite Elastic Medium. (Relative inclusion and matrix properties are those of the SiC/CAS material investigated)



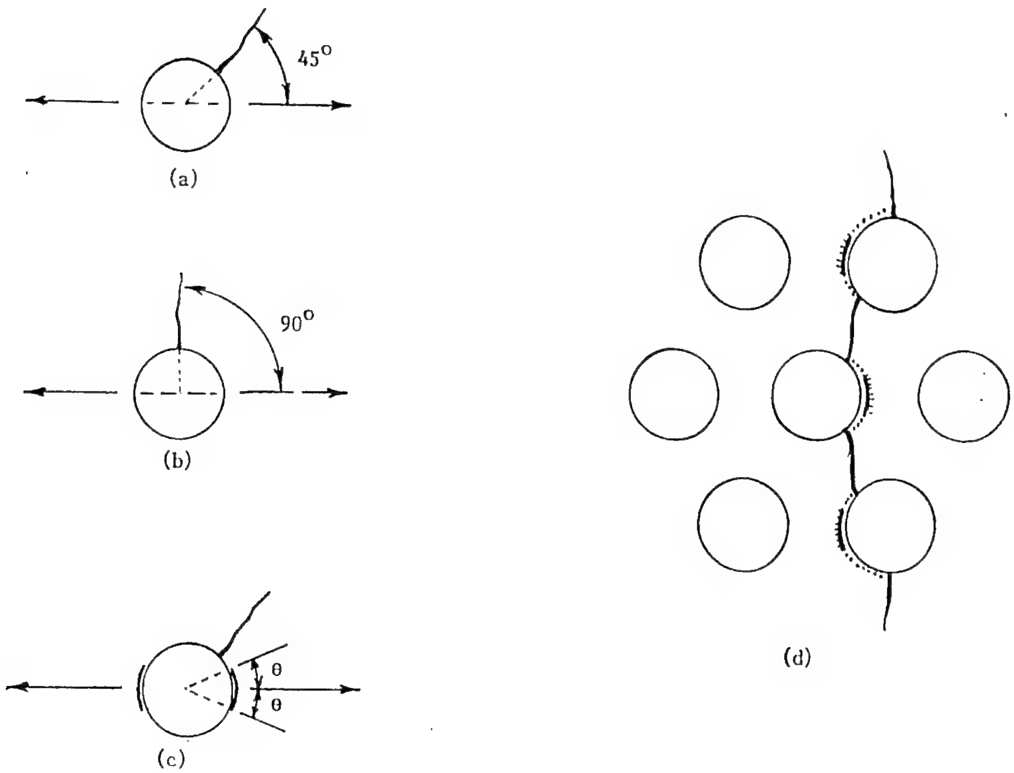
A

B

C

D

Photomicrographs of failure mechanisms in $[90_8]$ SiC/CAS specimen under transverse tensile loading



Development of failure mechanisms in transversely loaded ceramic matrix composite (a) initial radial cracks around closely packed fibers, (b) initial radial cracks around isolated fibers, (c) interfacial cracks, and (d) interconnection of radial and interfacial cracks

STRESS ANALYSIS FOR INTERFACIAL DEBONDING IN UNIDIRECTIONAL FIBER REINFORCED COMPOSITES

R. Chao and N. Laws

Department of Mechanical Engineering
University of Pittsburgh
Pittsburgh, PA 15261

ABSTRACT

This paper is devoted to the analysis of some two-dimensional problems associated with debonding at a fiber matrix interface in undirectional fiber reinforced composites. Thus consider first a single fiber surrounded by an isotropic matrix, and suppose that fiber-matrix debonding has occurred at the interface. The composite system may be subject to loading at infinity and over the surfaces of the interfacial cracks. As is well known, such problems are readily formulated using complex variable methods [1]. Ultimately these problems may be reduced to a pair of coupled Hilbert problems and solved by standard methods [1].

For illustration, consider a single interfacial crack which is opened by uniform pressure. The linear elastic solution is known to involve overlapping at the crack tips. Unfortunately the literature contains inconsistent solutions of the problem. The differences are identified and clarified.

Some recent work by Rice [2] and by Suo and Hutchinson [3] enables us to interpret the solution in proper perspective. In particular we can identify the significant parameters for interfacial debonding, Fig. 1. It is noteworthy that the calculated values for the classical stress intensity factors are virtually unaltered for most of the current ceramic matrix systems. Further, these results are compared with results obtained by assuming both fiber and matrix to have identical elastic moduli, Fig. 2.

Results for various loads and crack systems are presented. Extensions to anisotropic fibers are also indicated.

The paper concludes with a discussion of the implications of the foregoing on the prediction of loss of stiffness due to interfacial cracking.

REFERENCES

1. N.I. Muskhelishvili, "Some Basic Problems of the Mathematical Theory of Elasticity," translated by J.R.M. Radok, R. Noordhoff Ltd., Groningen.

2. J.R. Rice, "Elastic Fracture Mechanics Concepts for Interfacial Cracks," J. Appl Mech. 98 (1988) 98.

3. Z. Suo and J.W. Hutchinson, "Sandwich Test Specimens for Measuring Interface Crack Toughness," J. Materials Science Engng. A107 (1989) 135.

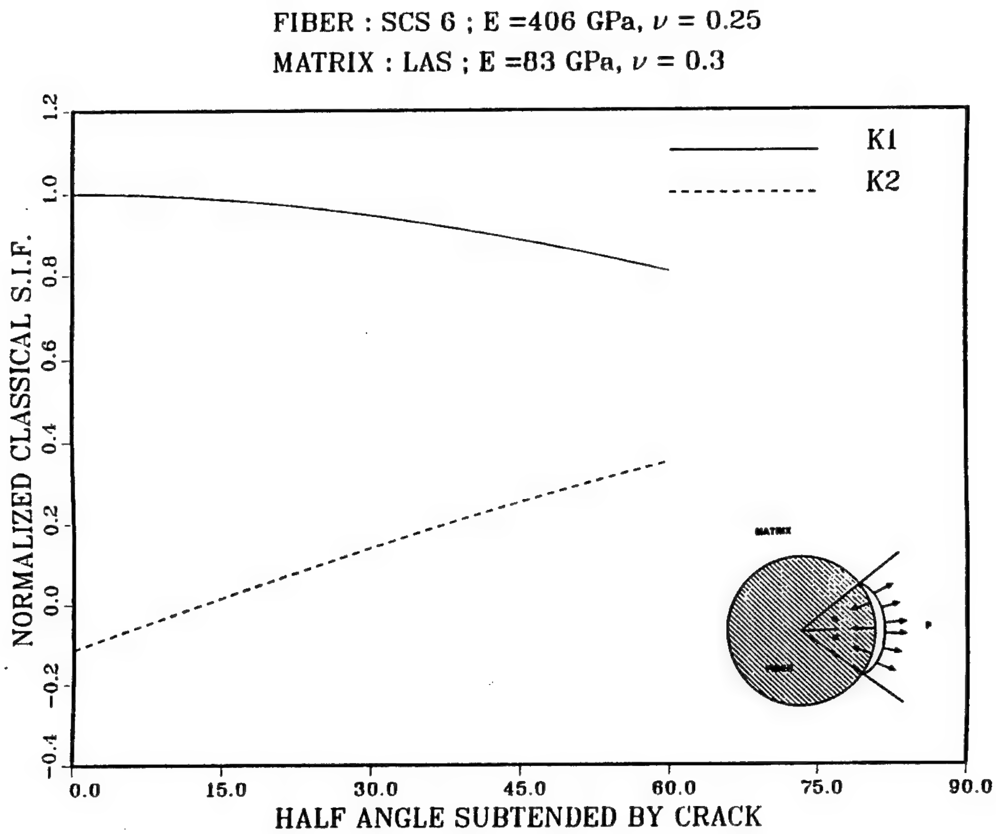

FIBER : SCS 6 ; E =406 GPa, ν = 0.25
MATRIX : LAS ; E =83 GPa, ν = 0.3
K1
K2
NORMALIZED CLASSICAL S.I.F.
HALF ANGLE SUBTENDED BY CRACK
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
0.0
15.0
30.0
45.0
60.0
75.0
90.0

Fig. 1.

FIBER : SCS 6 ; E =406 GPa, ν = 0.25

MATRIX : LAS ; E =83 GPa, ν = 0.3

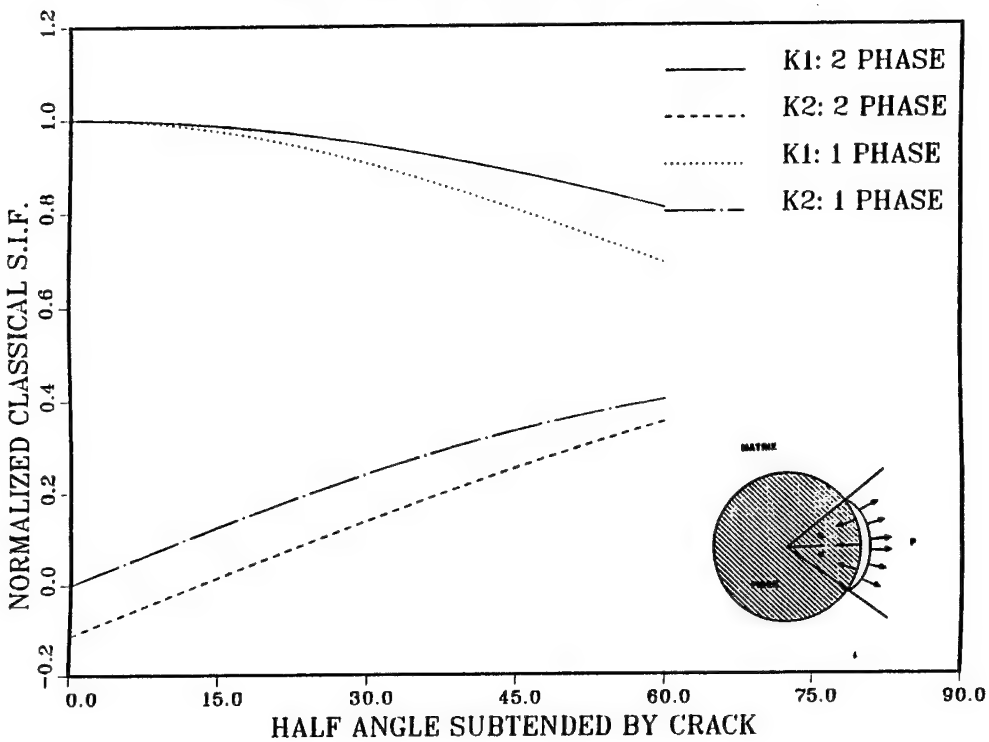


Fig. 2.

BRITTLE FIBRE DEBONDS AND COMPOSITE STRESS-STRAIN CURVES

M.R. Piggott

Advanced Composites Physics & Chemistry Group
Department of Chemical Engineering and Applied Chemistry
University of Toronto, Toronto, Ontario M5S 1A4

ABSTRACT

The integrity of the fibre-matrix interface plays a major role in achieving the properties required when fibre reinforced plastics are used for load bearing applications When making a composite, the fibres are usually coated prior to embedment in the matrix. The coating assures good adhesion to the polymer and also protects the fibres. It produces an interphasial region which has different properties from either fibre or matrix. Although much work has been done on the interphase, we still have little firm data on it, and have not yet established the appropriate conditions for brittle and ductile failure of the interphase. In addition "critical" composites, made to test traditional fibre reinforcement theory,have produced results which do not fit the theories. In this paper the theory is extended to include the case of fibres with initially debonded ends. (Such debonding could take place during manufacture.) It is shown that such debonding will lead, in certain circumstances, to straight line stress-strain plots, as required by the experiments. However, there are some inconsistencies in the debonded lengths estimated from the experiments, so further work is needed.

1. INTRODUCTION

It has always been believed that we understand reasonably well how fibre composites work. A look at four quite diverse texts on composites, ranging from quite old [1], to fairly old [2] and more recent [3,4] leaves little doubt that properties are quite well explained on the basis of interfacial shear stresses transferring forces from the matrix to the fibre.

Unfortunately, very few critical experiments have been carried out. These require composites containing fibres that are aligned and at the same time short enough to show effects due to friction at the interface. Some early work was claimed [5] to show the curved stress vs strain plots predicted, but this was not maintained in a later paper [6] and careful experiments with carbon-epoxies have shown that straight lines are obtained, even with fibres only 1 mm long: see fig. 1 [7]. Curves were only observed when the fibres had their adhesion destroyed by coating them with silicone oil, before embedding them in the plastic.

At about this time, it was shown [8] that the interphase did not necessarily fail when the maximum shear stress there reached the matrix shear strength. This observation came from experiments in which single fibres were embedded in blocks of polymer, and pulled out under stringent conditions. Fig. 2 shows a typical pull out curve obtained with a glass fibre embedded to a depth of 0.78 mm. It may be seen that the force rises to a maximum, F_A, at which point the adhesion fails. The fibre is then pulled out against friction generated by the polymer shrinkage pressure P_o and the interfacial coefficient of friction μ. When F_A is plotted vs embedded length, and the results compared with the values of F_A estimated from the maximum stress that the interface and adjacent region could exert, i.e. the matrix shear strength, the stress criterion appears not to produce a high enough result, or a suitable variation of F_A with embedded length, L. Instead, F_A was found to be approximately proportional to $L^{1/2}$, fig. 3, suggesting a brittle fracture process, analogous to that proposed by Griffith for brittle materials containing cracks [9]. We can estimate the work of fracture of the interphase, G_i, from fig. 3 using equation 1 [10]:

$$F_A = \pi d \sqrt{G_i L E_{fm}} \qquad (1)$$

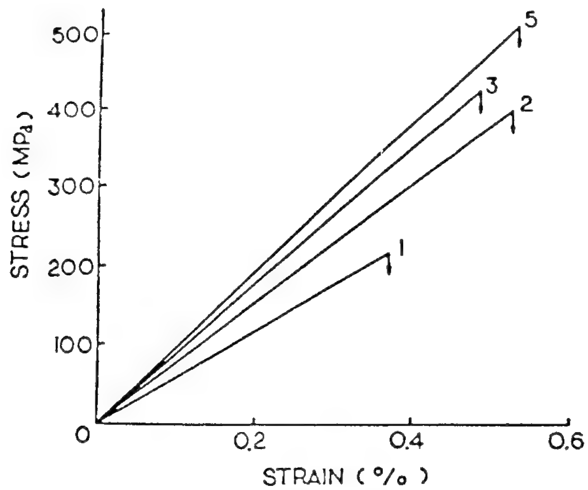


Fig. 1. Stress-strain curves for composites made with aligned short fibres (Union Carbide carbon) having aspect ratios of 125, 250 and 625.

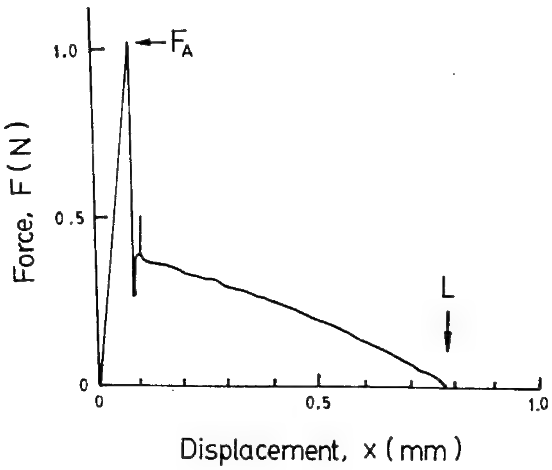


Fig. 2. Force required during the pulling out of a single glass fibre from a polyester matrix, plotted vs pulled out distance. Embedded length about 0.78 mm.

In this equation, d is the fibre diameter and E_{fm} depends on the Young's moduli of fibres and matrix E_f and E_m

$$E_{fm} \cong 0.33 \sqrt{E_f E_m} \qquad (2)$$

(The constant 0.33 arises from the geometry of the test specimen [10].

The idea of a brittle fracture criterion for interphase failure can also be applied to the composite. We thus have two possible failure criteria.

(1) There must be enough stress for the material's resistance to be overcome (i.e. the maximum interfacial shear stress must be sufficiently great to exceed the shear strength of the matrix, or the shear strength of the bond, whichever is the smaller). For a well bonded composite, this gives, for the composite strain at the onset of yielding [11]:

$$\varepsilon_{1\tau} \cong 2\tau_{mu} / \sqrt{E_f E_m} \qquad (3)$$

where τ_{mu} is the shear strength of the polymer matrix.

(2) There must be enough energy in the composite for interphase failure to be initiated. This energy criterion gives a composite strain for fibre debonding [8]:

$$\varepsilon_{1G} \cong \sqrt{8G_i / dE_f} \qquad (4)$$

For carbon fibres in epoxy, even though G_i is very small (about 20 Jm^{-2}), ε_{1G} is about three times $\varepsilon_{1\tau}$ (τ_{mu} is about 40 MPa, $E_f \cong 250$ GPa and $E_m \cong 2.5$ GPa; d = 8 μm). Thus the energy criterion is the critical criterion in the carbon fibre composite, rather than the stress criterion.

These results provide a possible explanation for the non-observance of curved stress-strain plots: interphase failure is delayed until the composite is almost at the fibre breaking strain. However, we have to look elsewhere to explain another observation made with the short carbon fibre reinforced epoxies. This was that the composite Young's modulus was reduced

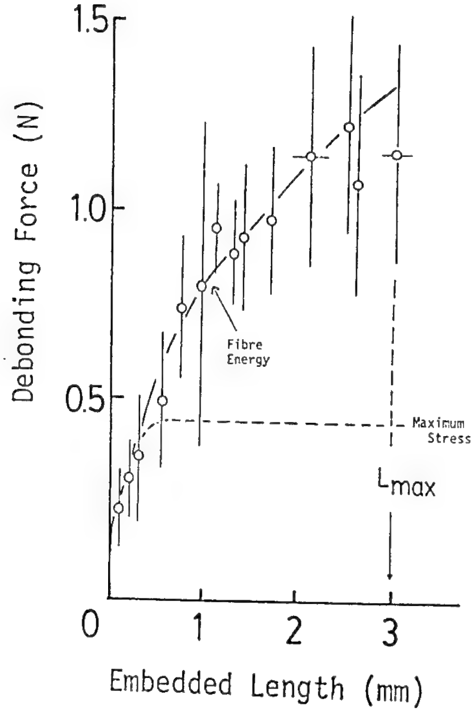


Fig. 3. Variation of debonding force, F_A with fibre embedded in polyester resin. Curve going through points is $F_A \propto L^{1/2}$. Dashed line is estimated result for maximum shear stress at interface high enough to equal shear strength of the polyester resin.

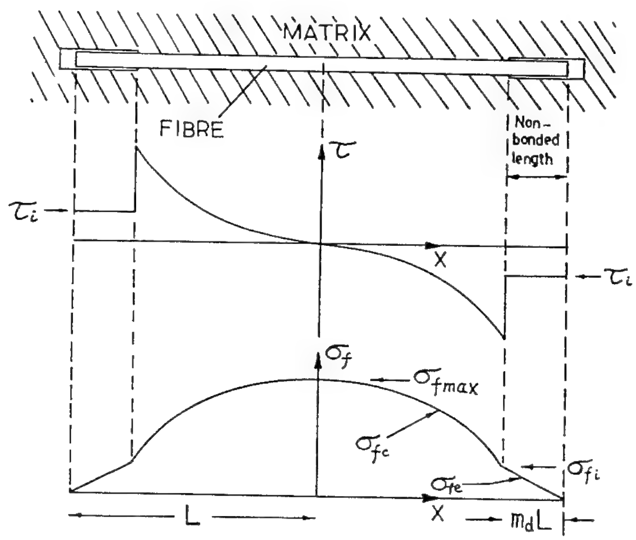


Fig. 4. Slip model for fibre with debonded ends: top; fibre showing slipped region: centre; interfacial shears: bottom; fibres stress.

when the fibres were treated in such a way as to reduce their adhesion, and increase s_c, before using them to make a composite [7].

In an attempt to explain this, we will consider fibres which have debonded ends [12]; such debonding has been observed in model composites [13].

2. SLIP THEORY FOR FIBRES WITH DEBONDED ENDS

Consider an element of the composite consisting of a single fibre surrounded by the immediately adjacent polymer matrix, which for simplicity is assumed to be a tube of circular cross section, fig. 4. Also, for simplicity the fibre will be considered to be symmetrically situated, with a stress along the direction of the fibre axis, and debonded regions of length m_dL at each end. 2L is the fibre length.

Stress transfer can take place due to elastic shears, and due to slip in the debonded region. As the stress applied to the composite is increased we can recognize four distinct regimes. 1) No slip; i.e. stresses are transferred by elastic shears at the interface. 2) Progressive slip in the debonded region; in this case the matrix starts slipping past the fibres near the fibre ends; the slipped region increases in length continuously. 3) Fixed slip in the debonded length; now the whole debonded region has slipped and the interface shears increase progressively without any change in the length of the slipped region. 4) Interphase failure, followed by further progressive slip; after the interphase fails, the whole fibre can slip. These four regimes are considered sequentially in what follows. Finally, composite failure is considered separately. Depending on fibre aspect ratio, and the initially debonded length, failure can occur in any of the stress regimes envisaged.

Regime 1. Elastic Stress Transfer

The governing equation for this may be written [3, p. 86]:

$$\sigma_1 = \left[V_f E_f (1\text{-}\tanh(ns)/ns) + V_m E_m\right]\varepsilon_1 \qquad (5)$$

where σ_1 and ε_1 are the stress and strain experienced by the composite in the fibre direction, V_f and V_m are fibre and matrix volume fractions, s is the fibre aspect ratio and n is a constant given by

$$n^2 = 2E_m/E_f(1+\nu_m)\ln(P_f/V_f) \qquad (6)$$

Here ν_m is the Poisson's ratio of the matrix, and P_f is a fibre packing factor, which is equal to $2\pi/\sqrt{3}$ for hexagonally packed fibres. (For V_f in the range 0.4 to 0.8, $n \cong \sqrt{E_m/E_f}$).

Since this is an entirely elastic situation, stress is proportional to strain, but when the fibres have finite (rather than infinite) length, the Young's modulus in the fibre direction, E_1, is somewhat less than that expected, based on the Rule of Mixtures, i.e.

$$E_1 = V_f E_f (1\text{-}\tanh(ns)/ns) + V_m E_m \qquad (7)$$

For continuous fibres, s tends to infinity, and we get the Rule of Mixtures

$$E_1 = V_f E_f + V_m E_m \qquad (8)$$

Stress transfer takes place through the agency of an interface shear τ_e which varies with distance from the fibre centre section, x, according to the equation

$$\tau_e = nE_f\varepsilon_1 \sinh(2nx/d)/2\cosh(ns) \qquad (9)$$

Fig. 5 shows the fibre stress and surface shears expected at this stage. The fibre has its maximum stress σ_{fmax} at the centre section, and

$$\sigma_{fmax} = E_f\varepsilon_1(1\text{-}\mathrm{sech}(ns)) \qquad (10)$$

In this regime, τ_e has its maximum value, τ_{emax} at the fibre ends (x = ± L):

$$\tau_{emax} = nE_f\varepsilon_1 \tanh(ns)/2 \qquad (11)$$

In order to keep the equations as simple as possible we will consider fibres longer than 0.5 mm, so that tanh(ns) ≅ 1.00, and sech(ns) is insignificant compared with 1.0.

Frictional shear stresses, τ_i, which are present when slip takes place, are determined by the coefficient of friction, μ, and the pressure across the interface P. P has two components, the cure shrinkage, P_o, and the matrix Poisson's shrinkage pressure, $\nu_1 E_m \varepsilon_1$. $\nu_1 \cong \nu_m/(1+\nu_m)$ (more detailed consideration gives some dependence of this pressure, and hence ν_1, on other elastic constants, and the fibre volume fraction [14,15]). We can neglect the fibre Poisson's shrinkage because the Young's modulus of the fibre is more than an order of magnitude (with carbon fibres it is two orders of magnitude) greater than that of the matrix. Thus

$$\tau_i = \mu(P_o + \nu_1 E_m \varepsilon_1) \qquad (12)$$

Slip starts when $\tau_{emax} = \tau_i$. It begins at the fibre ends and gradually extends as the composite strain increases, until it encompasses the whole debonded region.

The strain for the start of slip, ε_{1s} is obtained by putting τ_i (equation 12) equal to τ_{emax} (equation 11 with tanh(ns) assumed equal to 1) and hence solving these equations. This gives

$$\varepsilon_{1s} = 2\mu P_o/(nE_f-2\mu v_1 E_m) \tag{13}$$

Regime 1 ends when ε_1 reaches ε_{1s}.

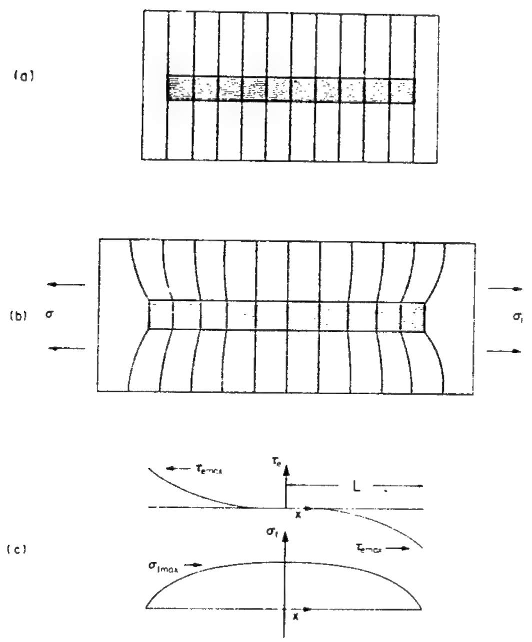


Fig. 5 Single fibre composite element. Elastic stress transfer gives shear stress and fibre stress variation along fibre as shown.

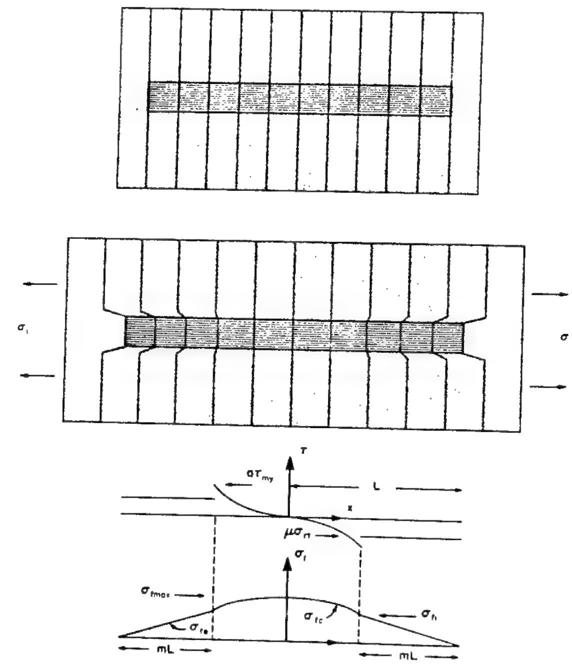


Fig. 6. Single fibre composite element. Stress transfer near ends is due to friction near centre it is elastic.

Regime 2. Progressive Slip in the Debonded Region

For strains greater than ε_{1s} a fraction m ($\leq m_d$) of the interface is slipping, fig. 6, and the stress-strain relation becomes [3, p. 92]:

$$\sigma_1 = (V_f E_f + V_m E_m)\varepsilon_1 - \frac{V_f}{s}\left[\frac{\tau_i}{n^2} + \frac{E_f^2 \varepsilon_1^2}{4\tau_i}\right] \tag{14}$$

with τ_i given by equation 12. m may be estimated from

$$m = E_f \varepsilon_1 / 2\tau_i s - 1/ns \tag{15}$$

When m reaches m_d, this regime ends. Putting m = m_d in equation 15 and using equation 12 for τ_i, we may estimate the strain, $\varepsilon_1 = \varepsilon_{1d}$, at this point:

$$\varepsilon_{1d} = \frac{2\mu P(m_d s + 1/n)}{E_f - 2\mu v_1 E_m (m_d s + 1/n)} \tag{16}$$

We have now established slip throughout the debonded region and regime 2 ends when $\varepsilon_1 = \varepsilon_{1d}$.

Regime 3. Fixed Slip in the Debonded Region.

Fig. 4 shows the regime considered. The end region has constant (frictional) shear stress while in the centre region the stresses are transferred elastically. The governing equation for the centre region may be written [3, p. 86]:

$$\sigma_{fc} = E_f\varepsilon_1 + B\sinh(2nx/d) + D\cosh(2nx/d) \tag{17}$$

B and D are constants determined by the boundary conditions $\sigma_{fc} = \sigma_{fi}$ at $x = \pm L(1-m_d)$. Substituting these values and evaluating B and D gives

$$\sigma_{fc} = E_f\varepsilon_1 + (\sigma_{fi}-E_f\varepsilon_1)\cosh(2nx/d)/\cosh(n\bar{s}) \tag{18}$$

where

$$\bar{s} = s(1-m_d) \tag{19}$$

To determine the response of the composite to an applied stress we need the average fibre stress. In the centre region this is σ_{fc} which is obtained by integrating equation 18 with respect to x between the limits 0 and $L(1-m_d)$ and dividing by $L(1-m_d)$. (Note that we are assuming that the debonded lengths are equal at the fibre ends, and all fibres have the same debonded lengths.) Thus we get

$$\bar{\sigma}_{fc} = E_f\varepsilon_1 + (\sigma_{fi}-E_f\varepsilon_1)\tanh(n\bar{s})/ns \tag{20}$$

Near the fibre ends

$$\sigma_f = 4\tau_i(L-x)/d \tag{21}$$

with τ_i given by equation 12. We can determine σ_{fi} by substituting $x = L(1-m_d)$, and equation 12, into equation 24.

$$\sigma_{fi} = 2m_d s\mu(P_o+\nu_1 E_m\varepsilon_1) \tag{22}$$

The average fibre stress in the end region is $\sigma_{fi}/2$. Thus

$$\bar{\sigma}_{fe} = m_d s\mu(P_o+\nu_1 E_m\varepsilon_1) \tag{23}$$

and we can now estimate the stress borne by the composite using the weighted averages of the stresses in fibres and matrix:

$$\sigma_1 = V_f\bar{\sigma}_f + V_m\bar{\sigma}_m \tag{24}$$

We assume that the matrix average tensile stress, $\bar{\sigma}_m$, is equal to $E_m\varepsilon_1$ and $\bar{\sigma}_f$ is determined from σ_{fc} (equation 20) and σ_{fe} (equation 23) in appropriate proportions. This gives the stress-strain relation

$$\sigma_1 = (V_fE_f+V_mE_m)\varepsilon_1+V_f\left[\mu(P_o+\nu_1E_m\varepsilon_1)(2m_d/n+m_d^2s) - (\varepsilon_1E_f/s)(m_ds+1/n)\right] \tag{25}$$

Regime 3 terminates when ε_1 reaches ε_{1G}. (For ε_{1G} see equation 4)

Regime 4: Slip After Interphase Failure

The regime considered at this stage is the same as that shown in fig. 6 with $m_d<m\leq 1$ (when m = 1, the whole fibre surface is slipping relative to the matrix).

(4a) For $m_d<m<1$ we use the stress-strain equation developed for the elastic-perfectly plastic matrix [3, p. 65] with τ_i given by equation 12:

$$\sigma_1 = (V_f E_f + V_m E_m)\varepsilon_1 - \frac{V_f E_f^2 \varepsilon_1^2}{4\mu s(P_o + \nu_1 E_m \varepsilon_1)} \qquad (26)$$

As m approaches 1, ε_1 approaches a new slip point, ε_{1p}. Now we can show that [3, p. 65]:

$$m = E_f \varepsilon_1 / 2s\tau_i \qquad (27)$$

Thus, for τ_i given by equation 12 substituting this in equation 27 and rearranging gives

$$\varepsilon_{1p} = \frac{2\mu s P_o}{1 - 2\mu s \nu_1 E_m / E_f} \qquad (28)$$

(4b) m = 1. Now σ_f cannot exceed $2ms\tau_i$ and $\bar{\sigma}_f$ is half the maximum fibre stress, i.e. $ms\tau_i$, so that

$$\sigma_1 = V_f s\tau_i + V_m E_m \varepsilon_1$$

and with τ_i given by equation 12 this comes to

$$\sigma_1 = V_f s\mu(P_o + \nu_1 E_m \varepsilon_1) + V_m E_m \varepsilon_1 \qquad (29)$$

Composite Failure

In principle, composite failure can occur at any stage. All that is required in stages 1, 2 and 3 is for the composite strain to reach the fibre breaking strain, ε_{fu}.

1. Failure during regime 1 requires $\varepsilon_{fu} < \varepsilon_{1s}$. Equation 7 then gives us composite failure when, writing $\sigma_{1u} = E_1 \varepsilon_{fu}$, we have, for the composite ultimate strength

$$\sigma_{1u} \cong V_f \sigma_{fu}(1 - 1/ns) + V_m E_m \varepsilon_{fu} \qquad (30)$$

2. Failure in regime 2 requires $\varepsilon_{1s} < \varepsilon_{fu} < \varepsilon_{1d}$. Then writing σ_{1u} for σ_1 in equation 14 given by $\varepsilon_1 = \varepsilon_{fu}$ we obtain

$$\sigma_{1u} \cong V_f \sigma_{fu}(1 - \sigma_{fu}/4\tau_i s) + V_f \tau_i / n^2 s + V_m E_m \varepsilon_{fu} \qquad (31)$$

with τ_i given by equation 12 with $\varepsilon_1 = \varepsilon_{fu}$.

3. Similarly, failure in regime 3 requires $\varepsilon_{1d} < \varepsilon_{fu} < \varepsilon_{1G}$, and equation 25 gives

$$\sigma_{1u} = V_f \sigma_{fu}\left[1 + \mu\nu_1 E_m(2m_d/n + m^2 s) - m_d - 1/ns\right] + V_f E_f \mu P_o (2m_d/n + m^2 s) + V_m E_m \varepsilon_{fu} \qquad (32)$$

4. In regime 4 we may expect more than one possible failure mode.

(a) For fibre failure we use equation 26 which gives for $\varepsilon_1 = \varepsilon_{fu}$

$$\sigma_{1u} = V_f \sigma_{fu}(1 - \sigma_{fu}/4\mu s(P_o + \nu_1 E_m \sigma_{fu}/E_f) + V_m E_m \sigma_{fu}/E_f \qquad (33)$$

This occurs for fibre aspect ratios greater than the critical.

(b) For fibre aspect ratios less than the critical, the matrix can slip past the fibres without breaking them, until its ductility is exhausted. Because of the stress concentrations introduced by the fibres, the fracture strain is difficult to estimate. Instead, the stress-strain curves are plotted up to about $2\varepsilon_{fu}$ using equation 29.

4. PREDICTED STRESS-STRAIN CURVES

Fig. 7 shows the stress strain curves obtained when this approximate analysis is applied to the carbon-fibre epoxy system investigated by Sanadi and Piggott [7]. We estimate the interfacial shear stress from the fibre critical aspect ratio measurements. Other parameters were obtained from single carbon fibre pull out studies [13], and must be regarded as tentative: i.e. shrinkage pressure, P_o = 21 MPa, and interphase work of fracture G_1 = 41 Jm^{-2}. It may be seen that the stress-strain plots are almost straight lines. (There is actually a slight "knee" at the end of regime 2). The different fibre aspect ratios give quite different slopes, and hence different apparent Young's moduli.

The Young's modulus may be estimated from equation 25. In this case, it reduces with sufficient accuracy to

$$E_1 = V_f E_f (1 - m_d - 1/ns) + V_m E_m \qquad (34)$$

since $E_1 = \sigma_1/\varepsilon_1$, and the frictional term may be neglected. Note that the fraction of fibre that has debonded, m_d, directly determines the extent of the deviation from the shear lag analysis.

We may use the results obtained by Sanadi and Piggott [7] to estimate m_d. We write

$$E_1 = \chi_1 \chi_2 V_f E_f + V_m E_m \qquad (35)$$

where χ_1 represents the effect on modulus of imperfect fibre alignment, and had the values 0.67 and 0.68 for 2 mm and 5 mm fibres respectively. χ_2 is the effect of finite fibre aspect ratio, and came to $(0.93 - m_d)$ for 2 mm fibres and $(0.97 - m_d)$ for 5 mm fibres. Using the experimental values for modulus reduction A_E, which should be equal to $\chi_1\chi_2$, we can estimate m_d. The results are given in table 1.

We can treat the results for strength similarly, since when the composite strain reaches the fibre breaking strain, ε_{fu}, we expect the composite to fail. Thus equation 25 gives, for $\varepsilon_1 = \varepsilon_{fu} (= \sigma_{fu}/E_f)$

$$\sigma_{1u} = V_f \sigma_{fu} (1 - m_d - 1/ns) + V_m E_m \sigma_{fu}/E_f \qquad (36)$$

Writing for Sanadi and Piggott's results [7]

$$\sigma_{1u} = \chi_3 \chi_4 V_f \sigma_{fu} + V_m E_m \varepsilon_{fu} \qquad (37)$$

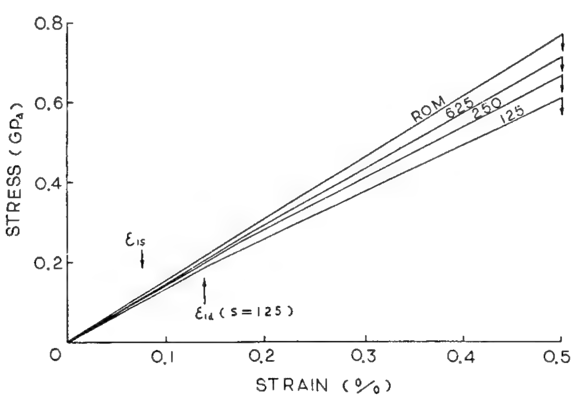


Fig. 7. Theoretical stress-strain curves, for composites made with aligned fibres having aspect ratios of 125, 250 and 625 (Union Carbide carbon P55S). Uppermost line is Rule of Mixtures. Initially debonded length is one tenth of total fibre length, P_o = 21 MPa, V_f = 0.4, s_c = 90, G_i = 40 Jm^{-2}.

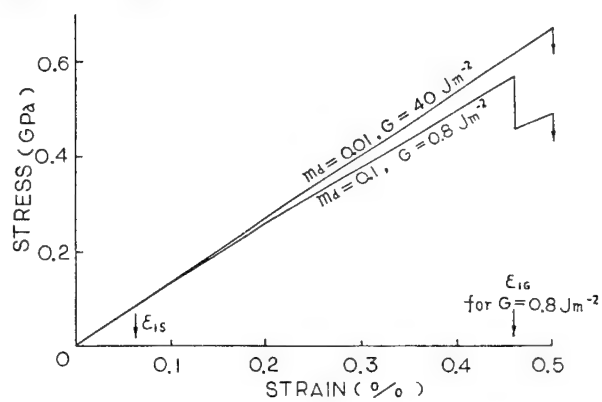


Fig. 8. Theoretical stress-strain curves. Union carbide P55S carbon fibres, with aspect ratios of 125, P_1 = 7 MPa, V_f = 0.4, s_c = 90.

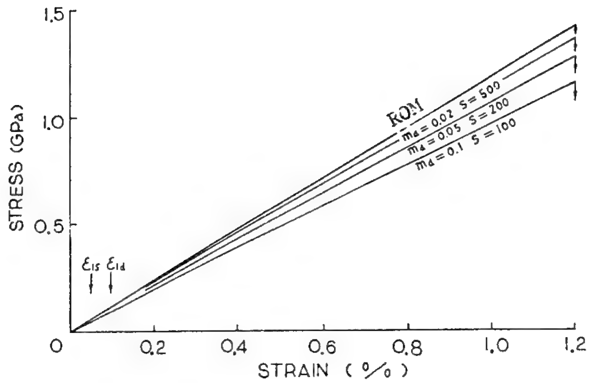


Fig. 9. Theoretical stress-strain curves. Hercules AS1 carbon fibres. P_o = 20 MPa, V_f = 0.5, s_c = 200, G_i = 40 Jm^{-2}.

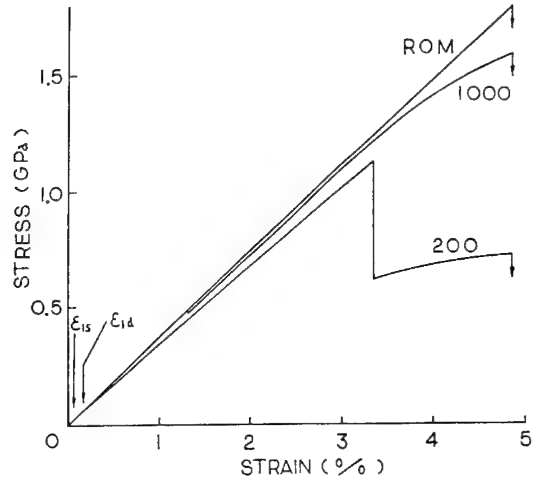


Fig. 10. Theoretical stress-strain curves for glass fibres, P_o = 20 MPa, V_f = 0.5, s_c = 200, G_i = 40 Jm^{-2}.

where χ_3 represents the effect of imperfect alignment, equal to 0.74 for 2 mm fibres and 0.76 for 5 mm fibres, χ_4 is the effect of fibre length, and has the same values as for the modulus. Using the strength results to estimate m_d gives the values shown in table. 1. These do not correlate with m_d estimated from the modulus, and in four cases no slip at all is indicated.

As indicated by their omission from equation 34, the effects of the critical aspect ratio, s_c, and the shrinkage pressure P_o are negligible. G_i has no effect, unless it is very small. Fig. 8 shows that, for G_i about 0.8 Jm^{-2} (i.e. about the level of ceramic materials such as glass) there is a sudden drop in stress when ε_{1G} is reached. ε_{1G}, given by equation 8, is reduced below ε_{fu} only when G_i is very small. Also shown in fig. 8 is the effect of reducing m_d.

Similar results are predicted for Hercules AS1 carbon fibre composites. Fig. 9 shows the stress-strain plots predicted for different fibre aspect ratios, again using data for carbon from Piggott et al [8]. The "knee" is even less pronounced in this case because of the larger breaking strain of the fibres (1.2% compared with 0.5%).

Glass fibres, which have even higher breaking strains, show strong debonding failure effects, fig. 10, when data from the same source is used. Because of this, the stress-strain plots are not very straight.

Table 1

Fibre Length (mm)	Surface Treatment	Estimated χ_2	m_d	Estimated χ_4	m_d
	sized	0.87	0.06	1.00	–
2	desized	0.66	0.27	0.82	0.11
	etched	0.66	0.27	0.82	0.11
	coated	0.37	0.56	0.62	0.31
	sized	0.99	0.02	1.21	–
5	desized	0.76	0.21	1.04	–
	etched	0.87	0.10	1.04	–
	coated	0.41	0.56	0.72	0.25

DISCUSSION AND CONCLUSIONS

A composite in which the fibres debond to some extent near the ends, during the manufacturing process, may have straight stress-strain plots, even though slip is taking place in the debonded region. The deviation from the elasticity equation (equation 7) depends directly on the fraction of fibre debonded, m_d, and is only significant (i.e. >1%) if $m_d > 0.01$ (see equation 34).

Complete debonding of the fibre can only occur if the work of fracture of the interphase is very low, or the breaking strain of the fibres is quite high. Thus, for carbon fibre composites it seems unlikely to occur at all, at least based on data presently available, while for glass fibre composites it could occur at a composite strain of about 60% of the fibre breaking strain. The drop in stress then predicted for relatively small fibre aspect ratios (e.g. s = 200) seems likely to result in complete composite failure, unless the stressing system is extremely stiff.

The effects of post debonding friction and matrix cure shrinkage pressure appear not to be very great.

The initial debonding concept, however, although predicting the straight stress-strain curves observed in short fibre composites, does not yield consistent values for the fraction of fibre debonded (see table 1). Thus, it is not an entirely satisfactory explanation of the experimental results so far obtained.

The most pressing need at the moment is for more, careful, experiments on aligned short fibre composites. In particular the effect of fibre breaking strain, and energy of debonding, needs to be investigated.

REFERENCES

1. N. J. Parratt, Fibre Reinforced Materials Technology, Van Nostrand Reinhold co., London, 1972.
2. J.E. Ashton, J.C. Halpin and P.H. Petit, Primer on Composite Materials, Technomic Publishing Co., Stamford, Conn., 1969.
3. M.R. Piggott, Load Bearing Fibre Composites (Pergamon, Oxford, 1980)
4. D. Hull, An Introduction to Composite Materials, Cambridge University Press, Cambridge, 1981.
5. W.H. Bowyer and M.G. Bader, J. Mater Sci., 7, 1972, p. 1315.
6. P.T. Curtis, M.G. Bader and J.E. Bailey, J. Mater Sci. 13, 1978, p. 377.
7. A.R. Sanadi and M.R. Piggott, J. Mater Sci., 20, 1985, p. 421.
8. M.R. Piggott, A. Sanadi, P.S. Chua and D. Andison, Int. Conf. on Comp. Interface, 1986, p. 109.
9. A.A. Griffith, Phil. Trans Roy Soc., A221, 1920, p 180.
10. M.R. Piggott and P.S. Chua, Ind. Eng. Chem. Prod. R/D, Vol. 26, No. 4, 1987, p. 672.
11. M.R. Piggott, Polymer Comp. 3, 1982, p. 179.
12. M.R. Piggott, Materials Forum 10, 1987, p 228.
13. N. Hadjis and M.R. Piggott, J. Mater Sci., 12, 1977, p. 358.
14. M.R. Piggott, J. Mater Sci., 13, 1978, p 1709.
15. R.D. Mooney and F.J. McGarry, Proc. 14th SPI Conf. Section 12E, 1959.

A C^0/C^{-1} HIGHER-ORDER DISPLACEMENT THEORY FOR LAMINATED COMPOSITE PLATES WITH PARTICULAR FINITE ELEMENT SUITABILITY

Alexander TESSLER and Erik SAETHER

U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, Massachusetts 02172-0001

ABSTRACT

Increasing application of composite materials in highly loaded structures necessitates improved stress and dynamic response analysis of thick laminates for strength and failure prediction. What distinguishes the mechanical behavior of "thick" composites from their "thin" counterparts are the through-thickness strain effects, both due to transverse shear and transverse normal modes of deformation. Whereas in thin laminates these effects are negligibly small as compared to the normal strains, in thick laminates, the transverse straining may be rather significant. Amplifying the importance of the transverse straining effects are the relatively low material compliancy and strength in the transverse direction. Thus, to adequately model the deformation of thick composites, an accurate bending/stretching higher-order theory including both transverse shear and transverse normal effects should be used.

From the perspective of a large-scale response simulation of composite structures, a need exists for efficient and robust bending finite elements (i.e., beams, plates, and shells) which can effectively account for the transverse deformation modes. To date, displacement based shear-deformable theories have proved particularly attractive for the finite element discretization due to the inherent C^0-continuity associated with the displacement variables and physically desirable Poisson boundary conditions. In contrast, higher-order bending theories have largely been unsuitable for the finite element approximation primarily because they usually involve a large number of variables (C^0 or higher continuity) and higher-order edge boundary conditions in excess of the Poisson conditions. It is a quest for a computationally viable higher-order laminate plate theory which retains the efficiency of shear-deformable theories but is devoid of the drawbacks of currently available higher-order theories is what motivated the present effort.

The paper discusses salient features of a variationally consistent 10th-order displacement theory for stretching and bending of laminated composite plates possessing seven displacement variables that require at most C^0 continuity. The present formulation is an extension of a recently developed homogeneous plate theory [1,2] to laminated composite plates [3].

Starting with a parabolic transverse displacement distribution and linear inplane displacement variations across the thickness, the methodology involves the derivation of field consistent transverse shear and transverse normal strains by way of a weighted averaging procedure and enforcement of traction boundary conditions an the top and bottom plate surfaces. Equations of equilibrium and appropriate natural boundary conditions are then obtained from the principle of virtual work resulting in a 4th-order theory for stretching, a 6th-order theory for bending, a 0th-order theory for transverse stretching, and the edge boundary conditions involving exclusively Poisson variables.

A qualitative assessment of the theory is demonstrated on the problem of static equilibrium of a carbon/epoxy [30/-30]s laminate under a sinusoidal normal pressure. This problem embodies such complicating features as a high material aspect ratio (longitudinal modulus/transverse modulus), significant property changes across ply boundaries and the inplane shear coupling. Both moderately thick and truly thick laminates are analyzed, and the results are compared with the corresponding solutions of classical laminate theory and exact elasticity theory [4].

Finally, the theory appears particularly attractive from the viewpoint of finite element approximations. The variational principle involves spatial gradients of five weighted-average displacements which not exceed order one. The implication is that these variables can be approximated with C^0-continuous functions. The remaining two (higher-order) displacements possess no gradients in the variational statement, thus

needing only C^{-1} continuity (i.e., these variables may be discontinuous across element boundaries). The obvious advantage of this latter aspect is that an effective element-level condensation of the two displacements is possible, thus enabling the reduction to the standard number of variables used in shear-deformable theories.

REFERENCES

1. Tessler, A., "An Improved Higher-Order Theory for Orthotropic Plates". Proc. 13th Annual Mechanics of Composites Review, 1988, pp. 59-65.

2. Tessler, A., "A Higher-Order Plate Theory with Ideal Finite Element Suitability", Comput. Meths. Appl. Mech. Engrg. (in review).

3. Tessler, A. and Saether, E., "Towards Efficient Finite Element Modeling of Thick Composites Based on Higher-Order Theory", Mechanics of Materials (in review).

4. Pagano, N.J., "Influence of Shear Coupling in Cylindrical Bending of Anisotropic Laminates," J. Composite Materials, 4, 1970, pp. 330-343.

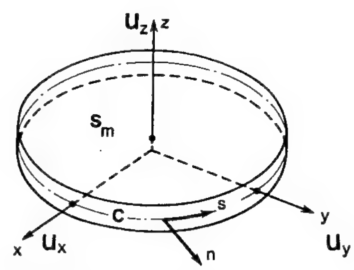
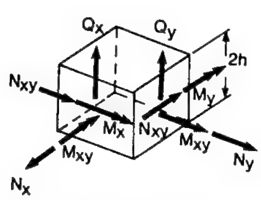
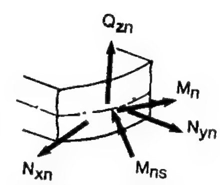


Plate coordinate system



Stress resultants and moments



Boundary forces and moments

DISPLACEMENT APPROXIMATIONS

$$u_x(x,y,z) = u(x,y) + hP_1(\xi)\theta_y(x,y)$$

$$u_y(x,y,z) = v(x,y) + hP_1(\xi)\theta_x(x,y)$$

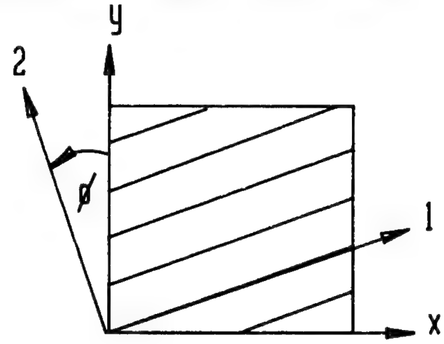
$$u_z(x,y,z) = w(x,y) + P_1(\xi)w_1(x,y) + [1/5+P_2(\xi)]w_2(x,y)$$

$P_n(\xi)$ = Legendre polynomials

$\xi = z/h \ \varepsilon[-1,1]$

2h = plate thickness

PLY PRINCIPAL MATERIAL DIRECTIONS (1-2)
IN RELATION TO LAMINATE COORDINATES (x-y)



CONSTITUTIVE RELATIONS FOR kth PLY

$$
\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix}^{(k)} =
\begin{bmatrix}
C'_{11} & C'_{12} & C'_{13} & 0 & 0 & C'_{16} \\
 & C'_{22} & C'_{23} & 0 & 0 & C'_{26} \\
 & & C'_{33} & 0 & 0 & C'_{36} \\
 & & & C'_{44} & C'_{45} & 0 \\
 & \text{(Symm.)} & & & C'_{55} & 0 \\
 & & & & & C'_{66}
\end{bmatrix}^{(k)}
\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{bmatrix}
$$

where

$$C'^{(k)}_{ij} = q_{im} q_{jn} C^{(k)}_{mn}$$

ACHIEVING "FIELD CONSISTENCY" IN TRANSVERSE STRAINING

- ASSUME FIELD-CONSISTENT GRADIENTS:

$$u^*_{i,z} = \sum_{j=0}^{M} a_{ij}(x,y)\, P_j(\xi) \quad (i=x,y,z), \quad M = \left[\begin{array}{ll} 2 & \text{for } i = x,y \\ 3 & \text{for } i = z \end{array}\right.$$

- SUBJECT TO:
  - TRACTION CONDITIONS ON S^+ & S^-:

$$\tau^{*(k)}_{iz} = \sigma^{*(k)}_{z,z} \Big|_{(k=1,N)} = 0 \qquad (i=x,y)$$

- EQUIVALENCE TO DIRECT GRADIENTS IN THE MEAN:

$$\min \int_{-h}^{h} (u^*_{i,z} - u_{i,z})^2\, dz \qquad (i = x,y,z).$$

FIELD-CONSISTENT TRANSVERSE STRAINS

$$\gamma^*_{xz} = k^2(P_0 - P_2)\,(w_{,x} + \theta_y)$$

$$\gamma^*_{yz} = k^2(P_0 - P_2)\,(w_{,y} + \theta_x)$$

$$\varepsilon^*_z = w_1/h + \sum_{j=1,2,3,6}^{3} \phi(\xi)_j\,\kappa_j$$

where

$$(\kappa_1,\ \kappa_2,\ \kappa_3,\ \kappa_6) = (\theta_{y,x},\ \theta_{x,y},\ w_2/h,\ \theta_{x,x} + \theta_{y,y})$$

$$\phi(\xi)_i = \frac{h}{6}\,\{P_2(\xi)\,r_i - [P_1(\xi)/14 + P_3(\xi)]\,k_3^2\,s_i\}$$

$$\phi(\xi)_3 = k_3^2\,[6P_1(\xi) - P_3(\xi)],\quad k_3^2 = 42/85$$

$$r_i = (C_{3i}/C_{33})^{(k=1)} - (C_{3i}/C_{33})^{(k=N)}$$

$$s_i = (C_{3i}/C_{33})^{(k=1)} + (C_{3i}/C_{33})^{(k=N)} \quad (i=1,2,6).$$

VIRTUAL WORK

$$\iiint_V (\sigma_{xx}\delta\varepsilon_{xx} + \sigma_{yy}\delta\varepsilon_{yy} + \sigma^*_{zz}\delta\varepsilon^*_{zz} + \tau_{xy}\delta\gamma_{xy} + \tau^*_{xz}\delta\gamma^*_{xz} + \tau^*_{yz}\delta\gamma^*_{yz})\,dxdydz$$

$$- \iint_{S^+} q^+\delta u_z dxdy - \iint_{S^-} q^-\delta u_z dxdy - \iint_{S_\sigma} (\bar{T}_x\delta u_x + \bar{T}_y\delta u_y + \bar{T}_z\delta u_z)\,dsdz = 0$$

Integrating across the plate thickness yields a 2-D virtual work statement:

$$\iint_{S_m} \Big\{ N_x\delta u_{,x} + N_y\delta v_{,y} + N_z\delta(w_1/h) + N_{xy}(\delta u_{,y} + \delta v_{,x})$$

$$+ M_x\delta\theta_{y,x} + M_y\delta\theta_{x,y} + M_z\delta(w_2/h) + M_{xy}(\delta\theta_{x,x} + \delta\theta_{y,y})$$

$$+ Q_x(\delta w_{,x} + \delta\theta_y) + Q_y(\delta w_{,y} + \delta\theta_x) - q_1(\delta w + \delta w_2/k^2) - q_2\delta w_1 \Big\}\,dxdy$$

$$- \oint_{C_\sigma} \Big\{ \bar{N}_{xn}\delta u + \bar{N}_{yn}\delta v + \bar{M}_{xn}\delta\theta_y + \bar{M}_{yn}\delta\theta_x + \bar{Q}_{zn}\delta w$$

$$+ \bar{Q}_{z_1}\delta w_1 + \bar{Q}_{z_2}\delta w_2 \Big\}\,ds = 0$$

EQUILIBRIUM EQUATIONS

$$(\delta u):\quad N_{x,x} + N_{xy,y} = 0$$

$$(\delta v):\quad N_{xy,x} + N_{y,y} = 0$$

$$(\delta\theta_y):\quad M_{x,x} + M_{xy,y} - Q_x = 0$$

$$(\delta\theta_x):\quad M_{xy,x} + M_{y,y} - Q_y = 0$$

$$(\delta w):\quad Q_{x,x} + Q_{y,y} + q_1 = 0$$

$$(\delta w_1):\quad -N_z/h + q_2 = 0$$

$$(\delta w_2):\quad -M_z/h + q_1/k^2 = 0$$

$$q_1 = q^+ - q^-, \quad q_2 = q^+ + q^-$$

POISSON BOUNDARY CONDITIONS

- **on C_1** (where stresses are prescribed):

$$N_{jn} = \bar{N}_{jn}, \quad M_{jn} = \bar{M}_{jn}, \quad Q_{zn} = \bar{Q}_{zn} \quad (j=x,y)$$

where

$$N_{xn} = N_x \ell + N_{xy} m, \quad N_{yn} = N_{xy}\ell + N_y m$$

$$M_{xn} = M_x \ell + M_{xy} m, \quad M_{yn} = M_{xy}\ell + M_y m$$

$$Q_{zn} = Q_x \ell + Q_y m, \quad \ell=\cos(x,n), \quad m=\cos(y,n)$$

with two higher-order shear resultants vanishing:

$$\bar{Q}_{z_1} = \bar{Q}_{z_2} = 0$$

- **on C_2** (where displ. are prescribed) :

$$u = \bar{u}, \quad v = \bar{v}, \quad \theta_y = \bar{\theta}_y, \quad \theta_x = \bar{\theta}_x, \quad w = \bar{w}$$

PLATE STRESS RESULTANTS

$$(N_x,\ N_y,\ N_z,\ N_{xy}) = \sum_{k=1}^{N} \int_{h_{k-1}}^{h_k} (\sigma_{xx},\ \sigma_{yy},\ \sigma_{zz},\ \sigma_{xy})\ dz$$

$$(M_x,\ M_y,\ M_z,\ M_{xy}) = \sum_{k=1}^{N} \int_{h_{k-1}}^{h_k} [(z\sigma_{xx} + \phi_1\sigma_{zz}),\ (z\sigma_{yy} + \phi_2\sigma_{zz}),\ (\phi_3\sigma_{zz}),\ (z\tau_{xy} + \phi_6\sigma_{zz})]\ dz$$

$$(Q_x,\ Q_y) = \sum_{k=1}^{N} \int_{h_{k-1}}^{h_k} k^2(P_0 - P_2)(\tau_{xz},\ \tau_{yz})\ dz$$

$$(\bar{N}_{xn},\ \bar{N}_{yn}) = \sum_{k=1}^{N} \int_{h_{k-1}}^{h_k} (\bar{T}_x,\ \bar{T}_y)\ dz$$

$$(\bar{M}_{xn},\ \bar{M}_{yn}) = \sum_{k=1}^{N} \int_{h_{k-1}}^{h_k} (\bar{T}_x,\ \bar{T}_y)\ z\ dz$$

$$(\bar{Q}_{zn},\ \bar{Q}_{z_1},\ \bar{Q}_{z_2}) = \sum_{k=1}^{N} \int_{h_{k-1}}^{h_k} \bar{T}_z(1,\ P_1,\ P_0/5 + P_2)\ dz$$

EQUILIBRIUM EQUATIONS IN DISPLACEMENTS

$$\mathbf{Q}\ \mathbf{L}_2\mathbf{u} = \mathbf{L}_1\mathbf{q}$$

$$\mathbf{w} = \mathbf{R}\ \mathbf{M}_1\mathbf{u} + \mathbf{S}\ \mathbf{q}$$

where

$\mathbf{Q}$, $\mathbf{R}$, and $\mathbf{S}$ Stiffness coefficient matrices
$\mathbf{L}_1$ and $\mathbf{M}_1$ are 1st order linear differential operators
$\mathbf{L}_2$ is a 2nd order linear differential operator, with

$\mathbf{q}^T = \{q_1, q_2\}$

$\mathbf{u}^T = \{u, v, w, \theta_x, \theta_y\}$

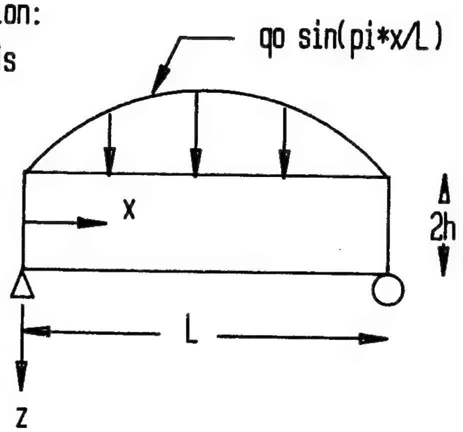
$\mathbf{w}^T = \{w_1, w_2\}$

COMPUTATION OF TRANSVERSE STRESSES

- DIRECTLY FROM CONSTITUTIVE RELATIONS (PRESENT-1)
- INTEGRATING 3-D ELASTICITY EQS OF EQUILIBRIUM (PRESENT-2)

A CARBON/EPOXY LAMINATE UNDER SINUSOIDAL PRESSURE

Lamination:
[30/-30]s



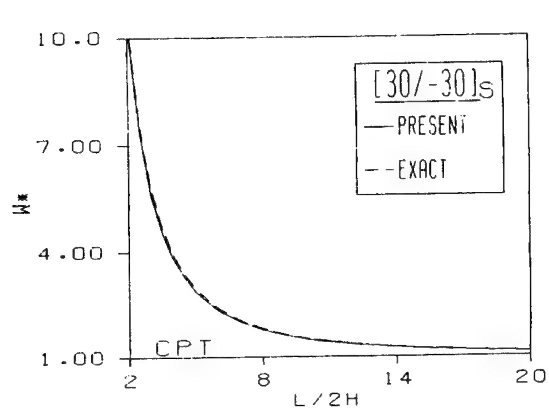
- The material properties:

$E_\ell = 25\text{x}10^6$ psi, $E_t = 10^6$ psi

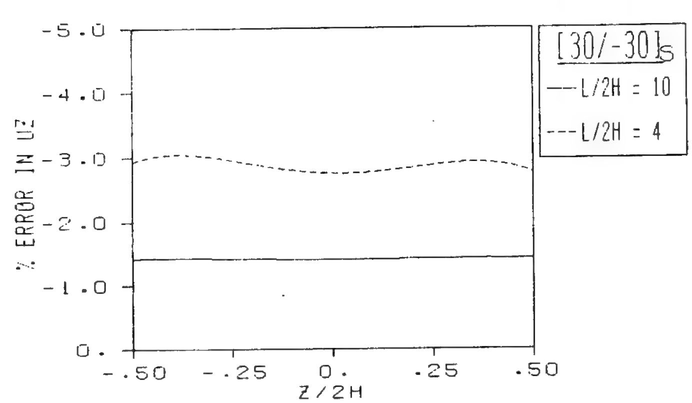
$G_{\ell t} = .5\text{x}10^6$ psi, $G_{tt} = .2\text{x}10^6$ psi

$\nu_{\ell t} = \nu_{tt} = .25$

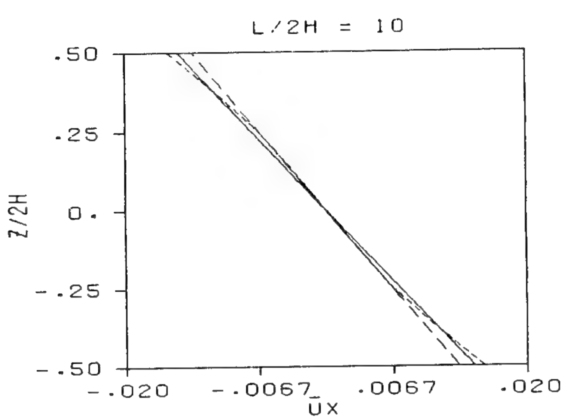
MAXIMUM MIDPLANE DEFLECTION

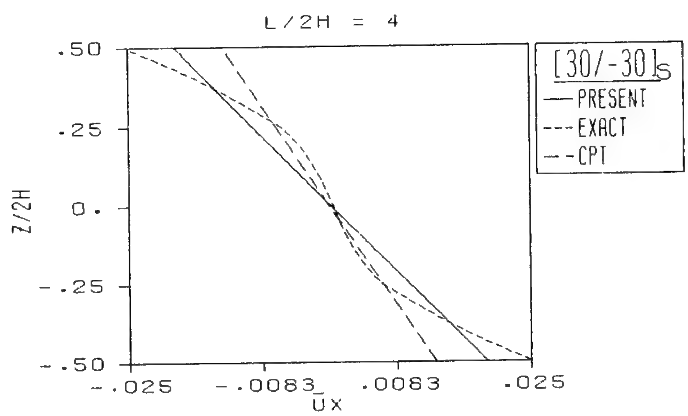


UZ DISTRIBUTION ACROSS THICKNESS

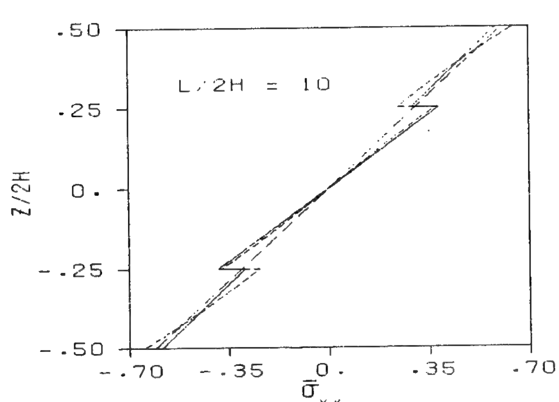


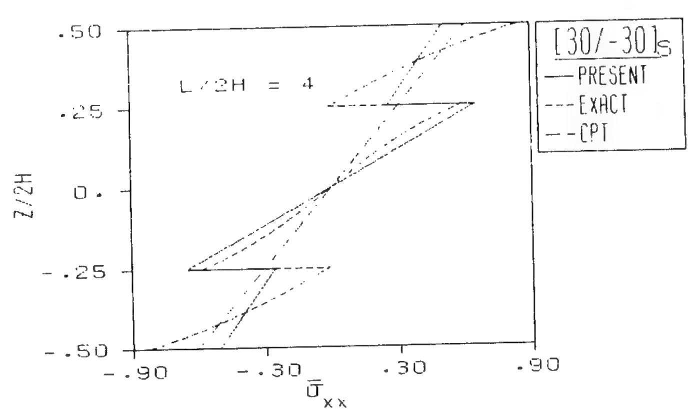
ŪX DISTRIBUTION ACROSS THICKNESS



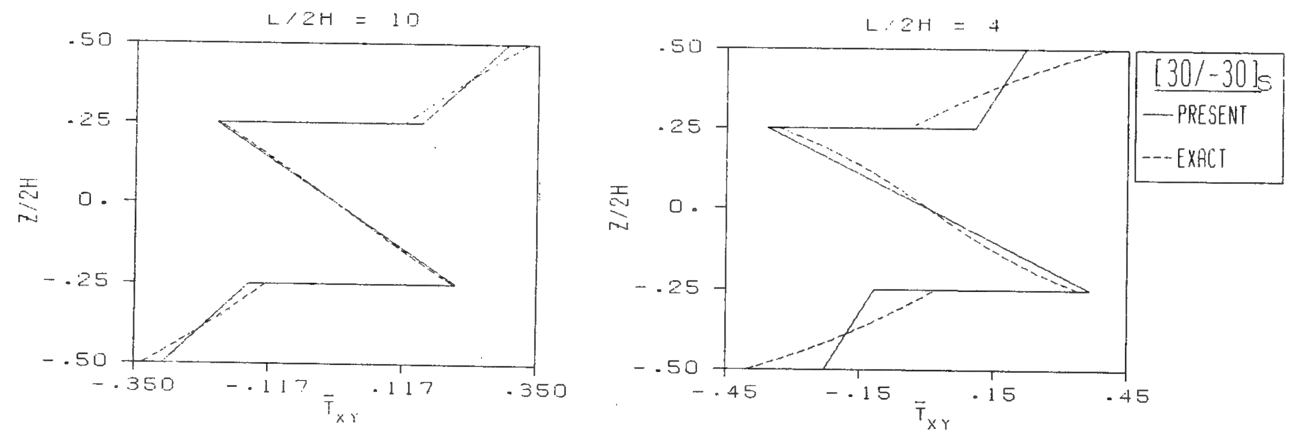


σ_{xx} DISTRIBUTION

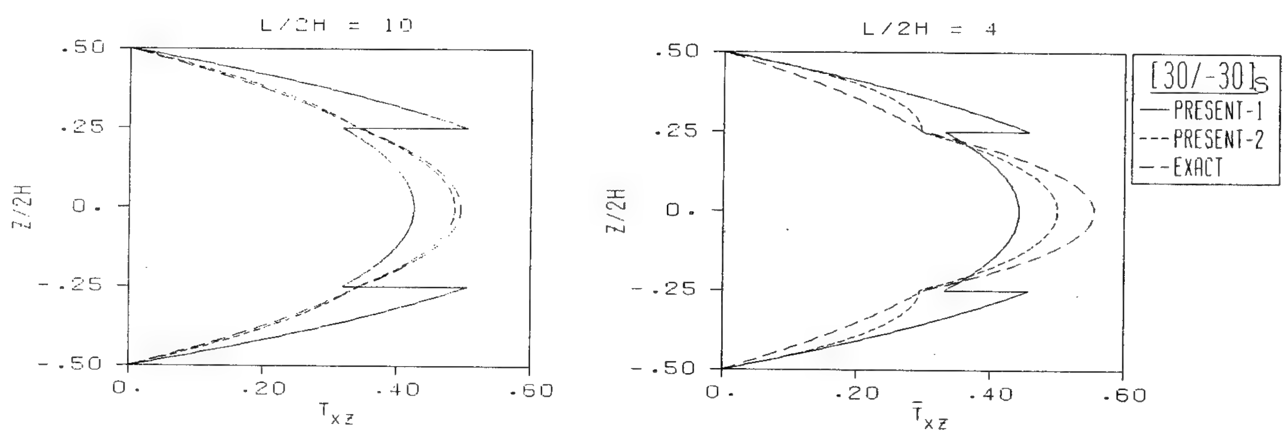




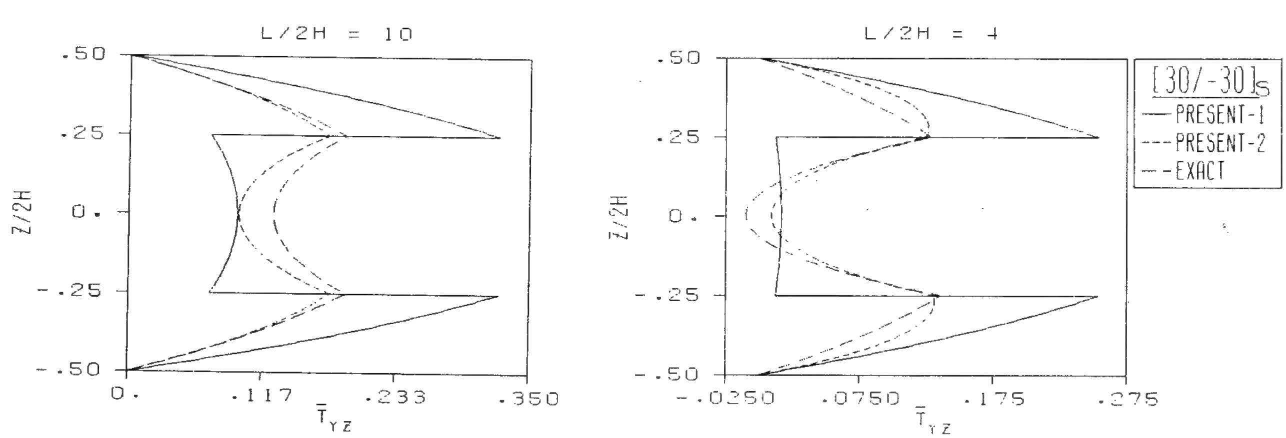
$\bar{T}_{xy}$ DISTRIBUTION



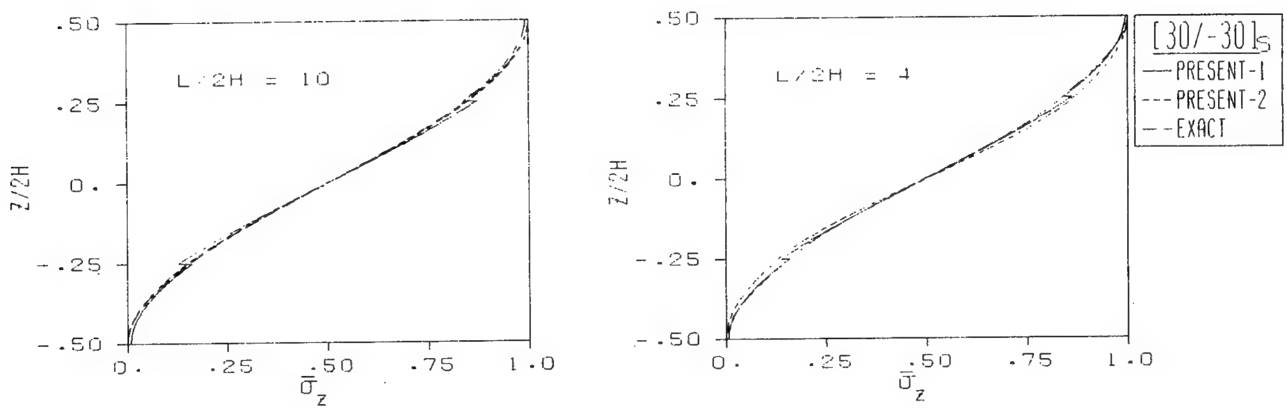
$\bar{T}_{xz}$ DISTRIBUTION



$\bar{T}_{yz}$ DISTRIBUTION



$\bar{\sigma}_z$ DISTRIBUTION



IDEAL FINITE ELEMENT APPLICABILITY

- SIMPLE & EFFICIENT ELEMENTS CAN BE GENERATED:

  C^0 continuity of u, v, w, θ_x, θ_y
  C^{-1} continuity of w_1, w_2

  I.E. 5 DOF PER NODE

- EXCLUSIVELY POISSON BC'S
- SAME COMPUTATIONAL EXPENSE AS REISSNER-MINDLIN PLATE ELEMENTS.

CONCLUDING SUMMARY

- 10TH-ORDER DISPLACEMENT THEORY:
  4TH-ORDER MEMBRANE THEORY
  6TH-ORDER BENDING THEORY
  0TH-ORDER TRANS. STRETCHING THEORY
- FIELD CONSISTENCY IN TRANSVERSE STRAINS ENSURING:
  - TRANSV. STRESSES SATISFYING TOP/BOTTOM TRACTION BOUNDARY CONDITIONS
  - NATURAL SHEAR CORRECTION FACTORS
  - POISSON BOUNDARY CONDITIONS
- 3-D DISTRIBUTIONS OF STRESSES
- THICK LAMINATE ANALYSIS CAPABILITY
- IDEAL SUITABILITY FOR FEM DISCRETIZATION

NONLINEAR MATERIAL BEHAVIOR IN $[(\pm45)_n]_s$ AND $[(0/90)_n]_s$ PIN-LOADED LAMINATES: AN EXPERIMENTAL AND FINITE ELEMENT APPROACH

S. M. Serabian

Mechanics and Structures Branch
Army Materials Technology Laboratory
Watertown, Massachusetts 02172

ABSTRACT

A host of investigators have made significant contributions in their attempts to understand the mechanical fastening of composite structures. A wide variety of approaches such as elasticity, finite and boundary element, geometric and interferometric moire, and ultimate strength testing have been employed to examine critical issues pertaining to joint structural integrity. The need for such efforts arises from trying to increase modeling capabilities to develop rational design guidelines. In this vein, the present paper attempts to quantitatively establish the effects of nonlinear intralaminar shear behavior on the modeling accuracy of $[(0/90)_n]_s$ and $[(\pm45)_n]_s$ pin-loaded laminates. The major thrusts of this self contained study may be classified by mechanical property characterization, linear and nonlinear finite element analysis, three dimensional experimental displacement contouring, and a qualitative material damage assesement [1].

Geometric moire was used to determine front surface, in-plane, experimental displacement contours of a $[(\pm45)_3]_s$ laminate configuration that was manufactured from 3M SP250-S2 glass fiber/resin system. Similar work on a $[(0/90)_3,0]_s$ laminate was accomplished by the author previously [2]. Out-of-plane displacement contouring of both laminate configurations was accomplished using a projection shadow moire technique. Fringe patterns throughout the load history of specimen up to incipient failure were obtained. Net and bearing section normal strains were obtained for the $[(\pm45)_3]_s$ using a C1000 HAMAMATSU digitizing unit.

Through thickness laminate mechanical properties were experimentally determined and used in conjunction with previously determined in-plane laminate mechanical properties [3]. A Modified three point bend test was used to obtain values of laminate transverse shear moduli while through thickness contraction measurements on laminate tension tests were employed to obtain estimates of their through thickness Poisson ratio values. Nonlinear crossply intralaminar shear behavior was determined from the ASTM D3518-76 specification.

Three dimensional constitutive equations for the $[(0/90)_n]_s$ laminate were developed from effective and actual lamina mechanical properties. A material axis transformation of these constitutive equations was employed to produce $[(+45/-45)_n]_s$ laminate constitutive equations. The validity of these constitutive equations and the effects of nonlinear intralaminar shear behavior were experimentally investigated through a comparison with uniaxial tension tests of both laminates. A sensitivity analysis of through thickness modulus was also done in this comparison in hope of providing further insight into the selection its magnitude.

Both linear and nonlinear three dimensional finite element approximations of the laminates were generated using the finite element code ABAQUS. Interactions between the pin and laminated coupon included pin elasticity and contact angle formation by using gap/interface elements between the meshes of both structures. Nonlinear intralaminar shear response was introduced through a classical Newton-Raphson approach in user material subroutines (UMAT). Laminate stresses, strains, and displacements were obtained at the pin-load levels of the moire study.

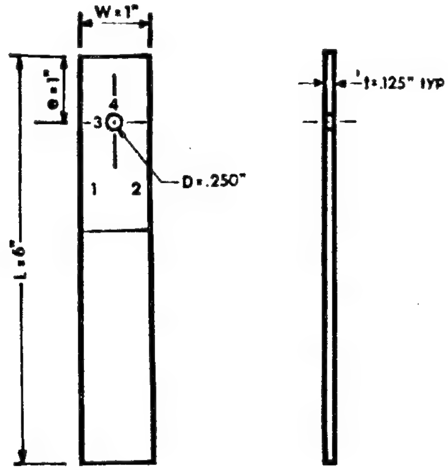
Comparisons of linear and nonlinear elastic finite element results show significant stress level reductions and increased strains values in $[(+45/-45)_3]_s$ laminate net and bearing sections. Similar results were observed in the $[(0/90)_3,0]_s$ laminate shearout section. Both pin proximity and load level intensified these effects. Net section $[(+45/-45)_3]_s$ experimental strains agreed well with nonlinear elastic finite element results at low pin load levels, but surpassed them at higher pin load levels. Both pin proximity and load level intensified these observations. Similar trends were observed in $[(+45/-45)_3]_s$ bearing and $[(0/90)_3,0]_s$ shearout sections, but were affected by unsymmetric experimental pin boundary conditions.

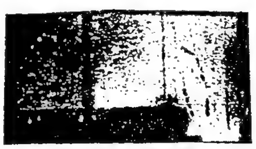
A qualitative determination of material damage within both pin-loaded laminates was done to investigate its possible role in the sectional strain comparison discrepancies. Liquid penetrant and a backlighting experimental arrangement was used to produce a planer view of progressive coupon damage for both laminate configurations. Results indicated material failure in those regions where experimental and nonlinear elastic finite element results diverged.

[1]Serabian, S. M., "An Experimental and Finite Element Investigation into the Nonlinear Material Behavior of Pin-Loaded Composite Laminates", *Doctoral Dissertation,* University of Massachusetts at Lowell, Lowell, MA, Fall 1989.

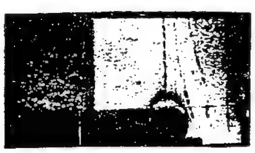
[2]Serabian, S. M. and Oplinger, D. W., "An Experimental and Finite Element Investigation into the Mechanical Response of $[(0/90)_n]_s$ Pin-Loaded Laminates", *Journal of Composite Materials*, 21, July 1987, pp.462-478.

[3]Serabian, S. M., "Comparisons of Finite Element Predictions and Experimental Results for $[(0/90)_n]_s$ Pin-loaded Laminates", *Masters Thesis,* University of Lowell, Lowell, MA, Fall 1985.





4673 N (1050 lbs)



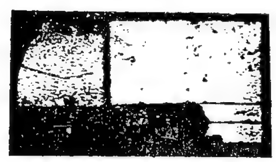
5341 N (1200 lbs)

6009 N (1350 lbs)

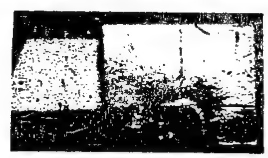
CONTOUR INTERVAL
.0254 mm (.001 in)

6676 N (1500 lbs)

$((0/90)_3\overline{0})_s$ OUT OF PLANE DISPLACEMENT CONTOURS



4451 N (1000 lbs)



5341 N (1200 lbs)

6231 N (1400 lbs)

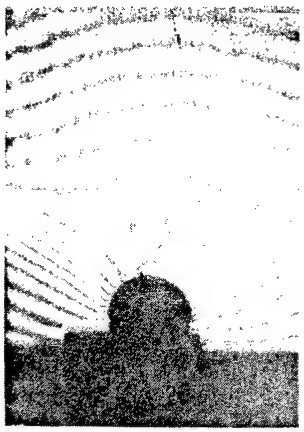
CONTOUR INTERVAL
.0254 mm (.001 in)

7121 N (1600 lbs)

$((\pm 45)_3)_s$ OUT OF PLANE DISPLACEMENT CONTOURS

$((45/-45)_3)_S$

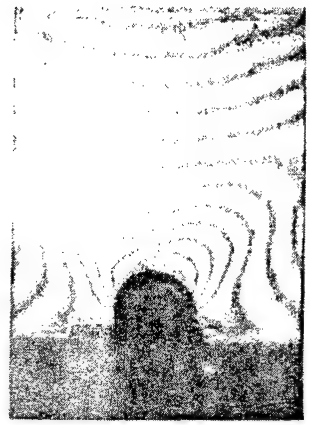
V FIELD



.010 TENSILE MISMATCH
.0254 mm (.001 in) CONTOUR INTERVAL

6005 N (1350 lbs)

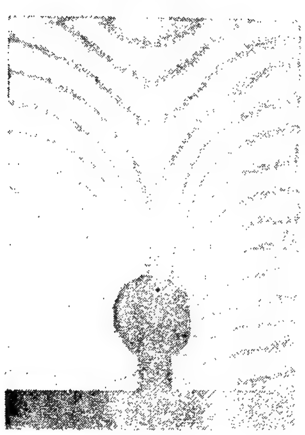
V FIELD



.010 COMPRESSIVE MISMATCH
.0254 mm (.001 in) CONTOUR INTERVAL

$((0/90)_3,\bar{0})_S$

V FIELD



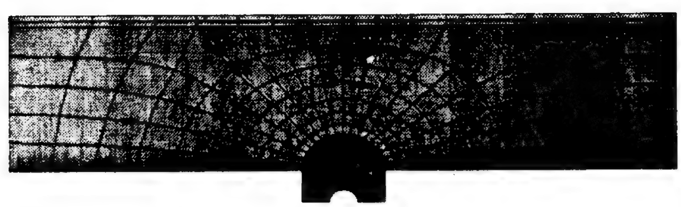
.008 TENSILE MISMATCH
.0254 mm (.001 in) CONTOUR INTERVAL

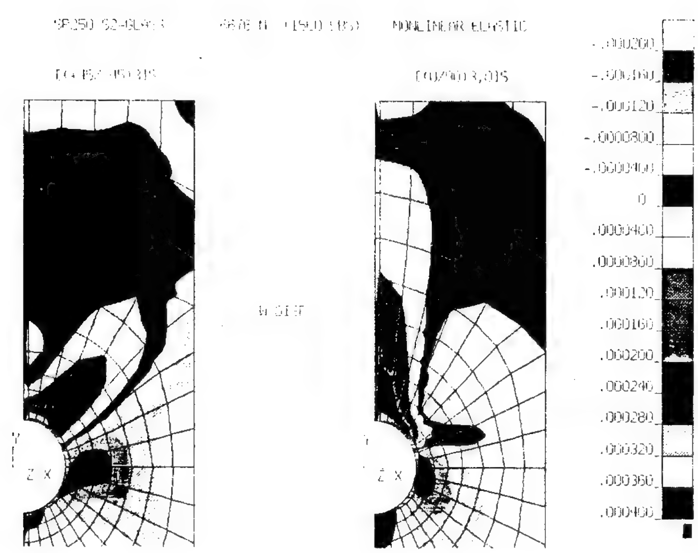
6672 N (1500 lbs)

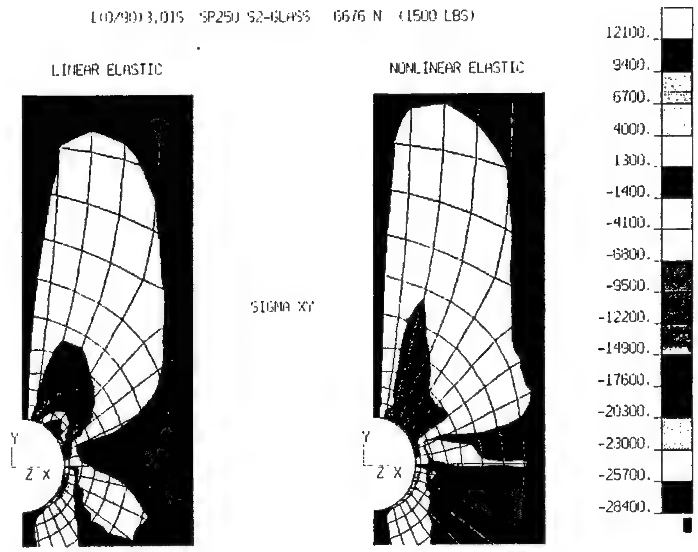
U FIELD

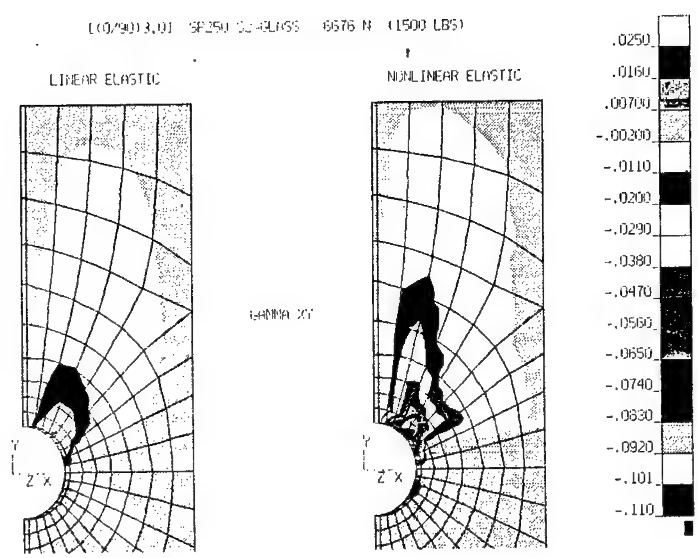
.008 TENSILE MISMATCH
.0254 mm (.001 in) CONTOUR INTERVAL

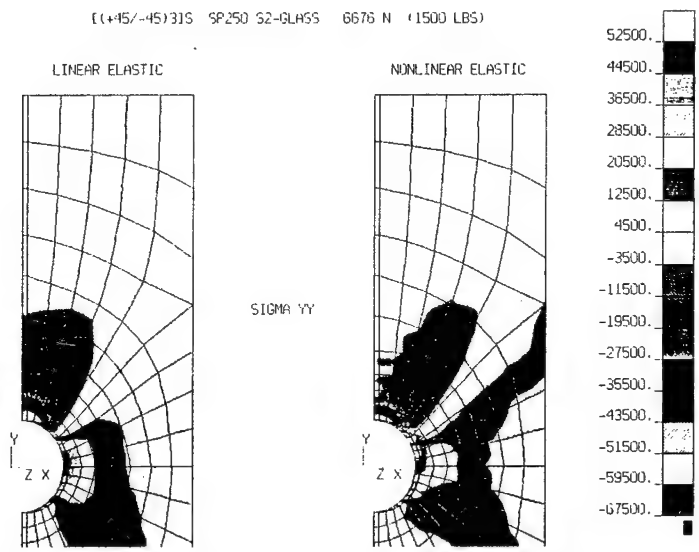
3D FINITE ELEMENT MODEL OF PIN-LOADED COUPON

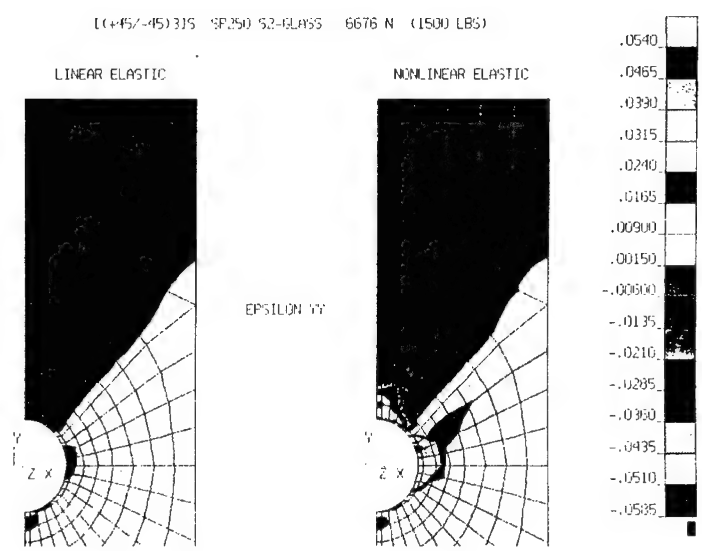




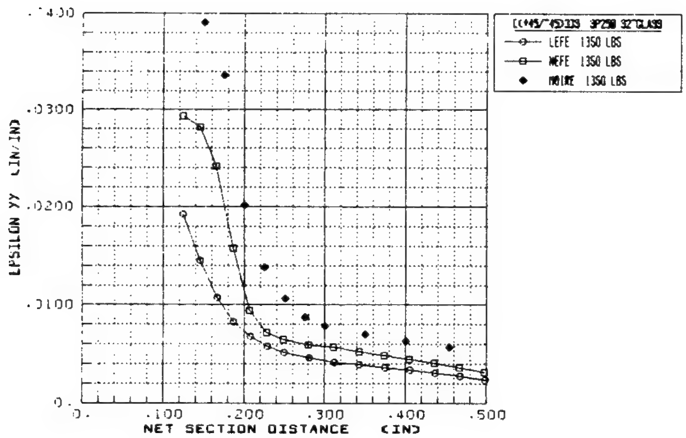

[(0/90)3,0]S SP250 S2-GLASS 6676 N (1500 LBS)
LINEAR ELASTIC
NONLINEAR ELASTIC
SIGMA XY
12100.
9400.
6700.
4000.
1300.
-1400.
-4100.
-6800.
-9500.
-12200.
-14900.
-17600.
-20300.
-23000.
-25700.
-28400.


[(0/90)3,0] SP250 S2-GLASS 6676 N (1500 LBS)
LINEAR ELASTIC
NONLINEAR ELASTIC
GAMMA XY
.0250
.0160
.00700
-.00200
-.0110
-.0200
-.0290
-.0380
-.0470
-.0560
-.0650
-.0740
-.0830
-.0920
-.101
-.110

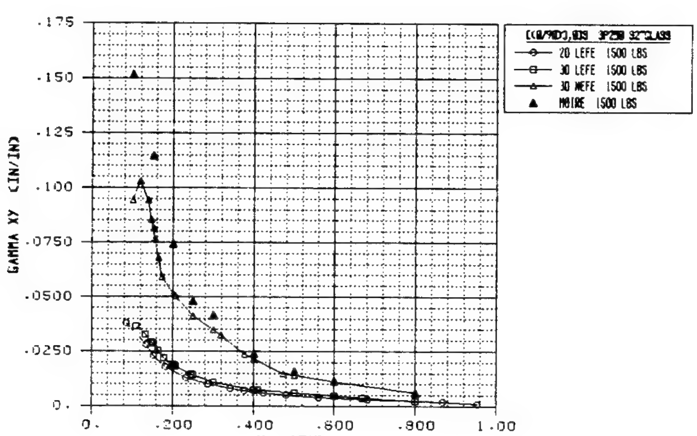

[(+45/-45)3]S SP250 S2-GLASS 6676 N (1500 LBS)
LINEAR ELASTIC
NONLINEAR ELASTIC
SIGMA YY
Y
Z X
52500.
44500.
36500.
28500.
20500.
12500.
4500.
-3500.
-11500.
-19500.
-27500.
-35500.
-43500.
-51500.
-59500.
-67500.


[(+45/-45)3]S SP250 S2-GLASS 6676 N (1500 LBS)
LINEAR ELASTIC
NONLINEAR ELASTIC
EPSILON YY
Y
Z X
.0540
.0465
.0390
.0315
.0240
.0165
.00900
.00150
-.00600
-.0135
-.0210
-.0285
-.0360
-.0435
-.0510
-.0585

[(+45/-45)3]S NET SECTION EPSILON YY FINITE ELEMENT/EXP MOIRE STRAINS



[(0/90)3,0]S MAXIMUM FINITE ELEMENT/EXP INTRALAMINAR SHEAR STRAINS
DV/DX AND DU/DY COMPONENTS



COMPRESSIVE FAILURE OF GRAPHITE FIBERS AND COMPOSITES

S. J. DeTeresa
Advanced Polymer Composites Group
Lawrence Livermore National Laboratory
University of California
Livermore, CA 94550

ABSTRACT

Recent advances in producing high tensile strength (HTS) graphite fiber composites have been overshadowed by an inability to achieve equivalent improvements in compressive strength. Considering the technological importance of advanced composites, it is highly desirable to reach a balance of composite properties. This goal requires a more complete understanding of compressive failure mechanism(s).

Analyses of the compressive failure of a unidirectional composite have led to numerous failure models and a correspondingly large list of factors predicted to be implicated in determining compressive strength. The size of this list is a good measure of the uncertainty in our understanding the failure of composites in compression. If composite compressive strength is limited by the strength of the fiber, then the only hope for improvement is with stronger fibers. Before embarking on expensive programs to investigate the effects of matrix properties, shape of fiber cross-section, fiber-matrix adhesion, etc. on composite strength, it is expedient to determine the inherent fiber compressive strength and thereby set the limit on the composite performance for a particular fiber.

A simple technique for determining the ultimate compressive strain of a single graphite filament is based on monitoring the deformation and failure using the piezoresisitive behavior of graphite fiber. Known compressive strains can be applied to the fiber by bonding it to the surface of a bulk compression specimen; thus the fiber is used as a strain gage in a manner that is completely analogous to the usage of metal foil strain gages. Compressive strains in the bonded filament are assumed to be equal to those on the surface of the compression specimen. The drastic resistance change that occurs when the fiber fails allows ultimate strains to be determined without tedious microscopic observations of the entire filament gage length.

Several HTS PAN-based graphite fibers were examined and all failed in a shear mode without any indication of fiber microbuckling. Average ultimate strains were all 2.8% or greater in magnitude. These values are nearly double those of the compressive failure strains of corresponding lamina. Therefore, it is concluded that the compressive strength of HTS graphite fiber composites is not limited by fiber strength. Consequently, experiments with composites containing a multiplicity of fibers must be conducted in order to determine why high fiber content composites fail at lower strains than single fiber "composites".

From a materials perspective, it is desirable to perform compressive tests on a sample that is free from the variability (particularly the imperfections) introduced by the technique used to process the composite. On the other hand, the sample should not be "idealized" to the extent where it has little or no resemblance to composite structures. A specimen that meets both of these criterion is also the most basic composite structure: an impregnated fiber strand. This material element is common to all graphite fiber composites regardless of the fabrication process. Consequently, the properties of an impregnated strand are more truly material properties than those of a lamina or any other larger composite specimen.

Impregnated 12K graphite fiber strands were fabricated in a manner that produced a uniform circular cross-section. Thus, the compressive strength of the strands could be measured by direct compression. Compressive loads were applied predominantly through the ends of the strands in order to avoid the complicating and detrimental effects of surface shear loading. Preliminary results indicate that the strands exhibit compressive strengths higher than those typically measured for larger composite specimens. Compressive strengths of strands fabricated from a common matrix material were insensitive to the type of HTS graphite fiber. However, there were significant differences in compressive strengths among strands fabricated from one fiber type and several matrix materials, all having virtually identical shear moduli.

COMPRESSIVE FAILURE OF GRAPHITE FIBERS AND COMPOSITES

Steven J. DeTeresa
Research Engineer
Advanced Polymer Composites Group

Lawrence Livermore National Laboratory

Fourteenth Annual Mechanics of Composites Review
October 31-November 1, 1989

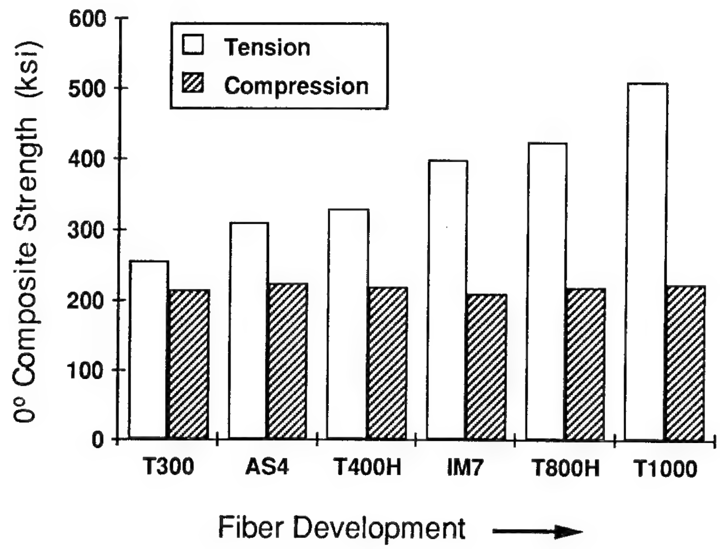
A Materials Science Approach to Compressive Failure

1. Proposed lamina compressive failure mechanisms

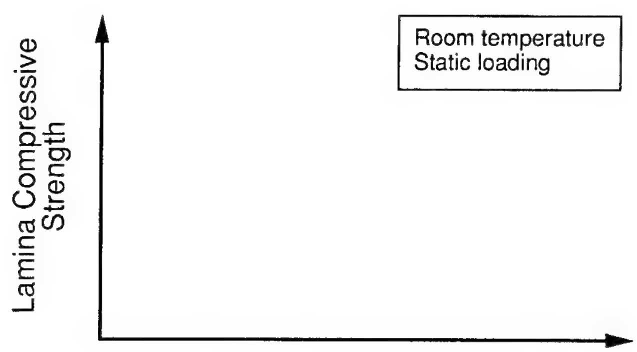
2. Single fiber compression

3. Composite compression

PAN-Based Graphite Fiber Development

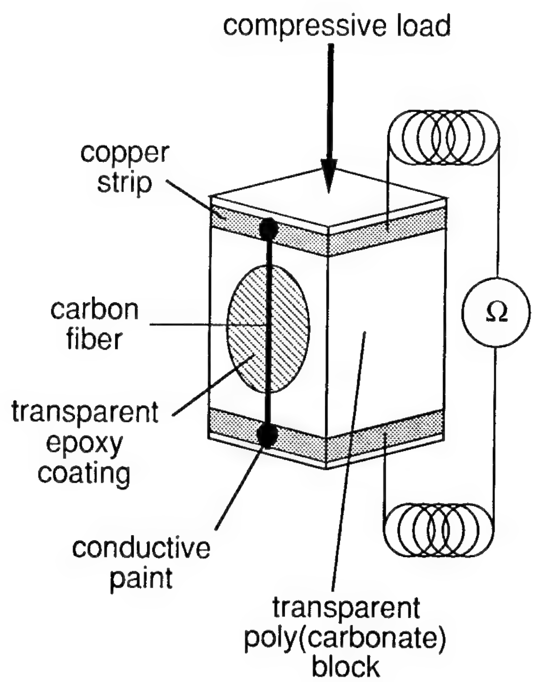


Lamina Compressive Strength

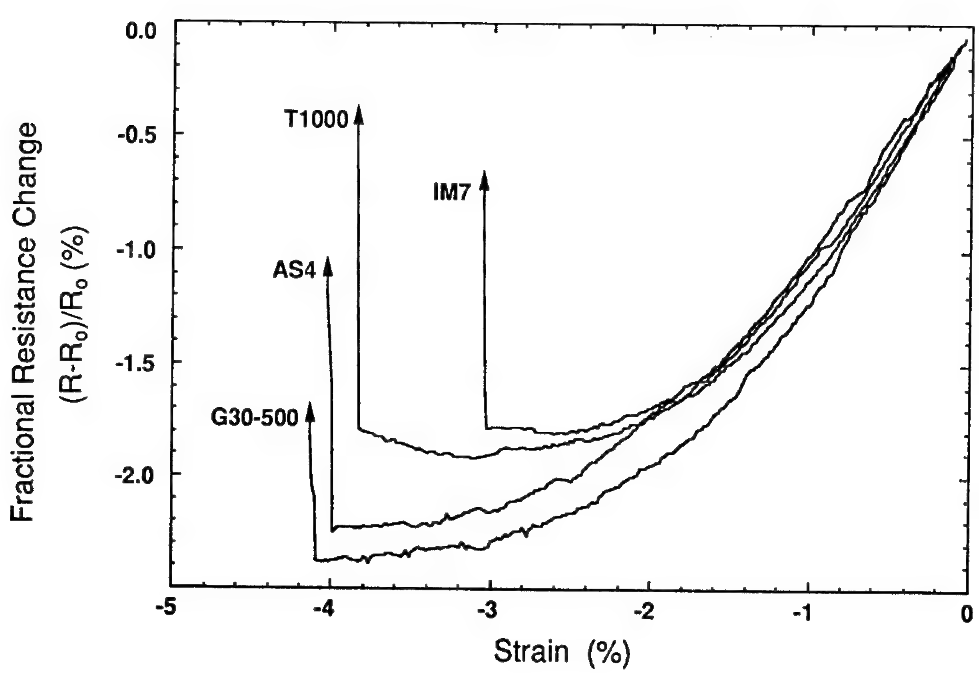


- Fiber volume fraction
- Matrix modulus
- Matrix yield strength
- Composite shear modulus
- Fiber compressive strength
- Fiber misalignment
- Fiber distribution
- Fiber diameter
- Fiber moment of inertia
- Fiber cross-sectional shape
- Void content
- Interlaminar shear strength
- Fiber-matrix adhesion
- Glass transition temperature
- Test method
- Fabrication method

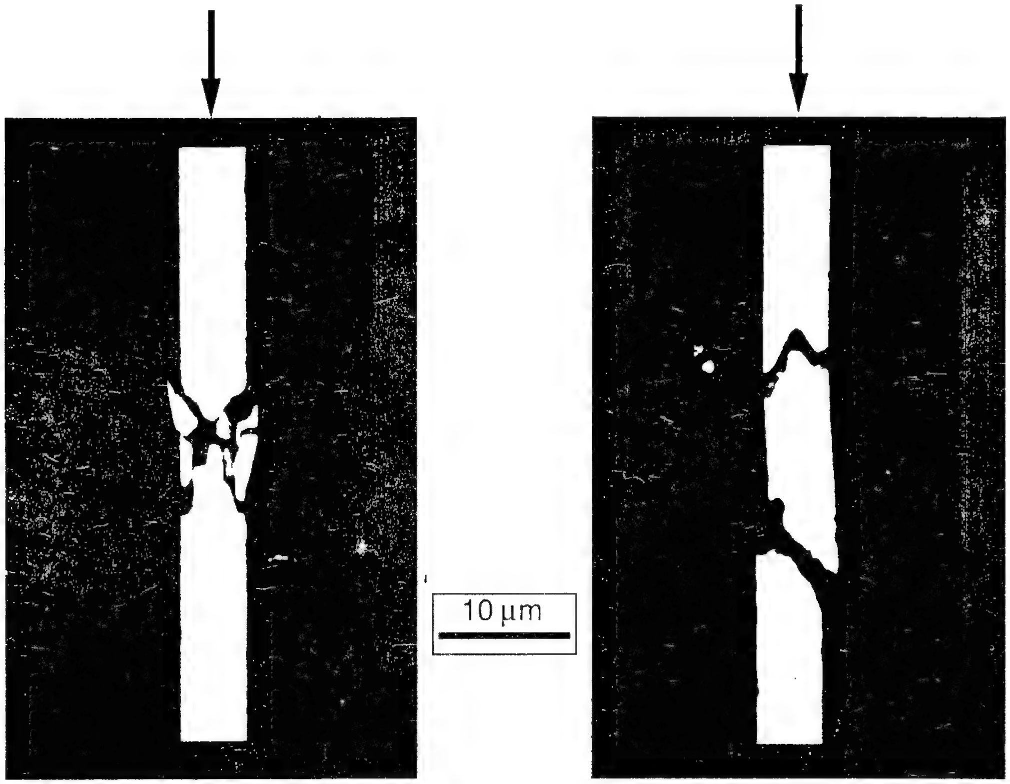
Schematic of Graphite Filament Compression Test



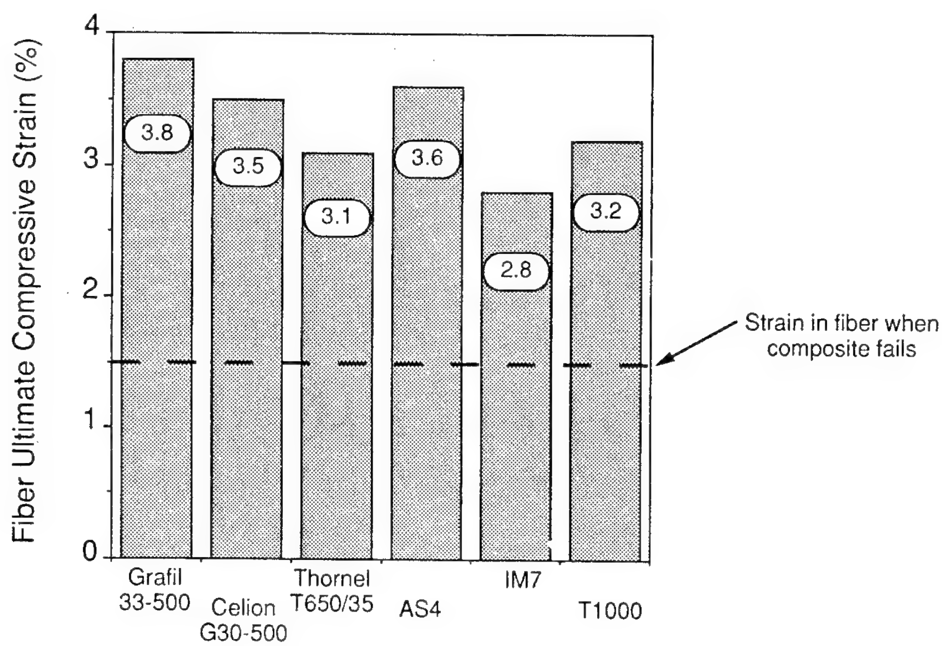
Detection of Compressive Failure in Single Filaments of PAN-Based Graphite Fiber



Compressive Fracture of PAN-Based Graphite Fiber



Ultimate Compressive Strains of Graphite Fibers

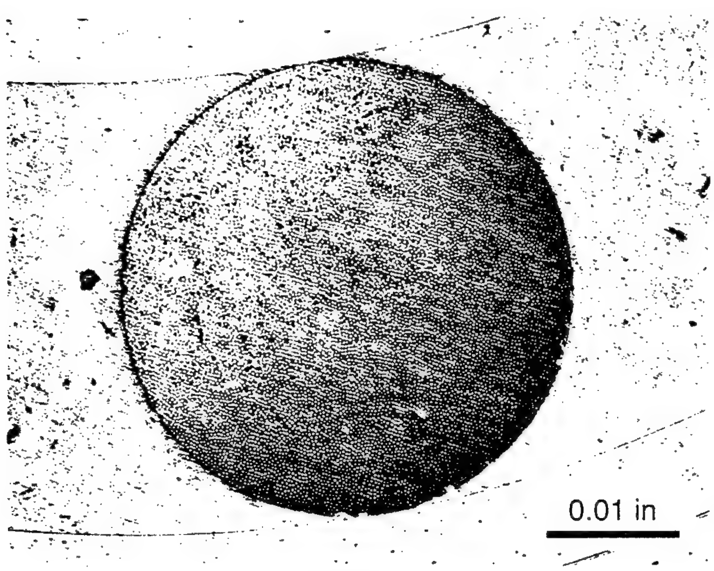


Composite Compressive Failure: Material Contribution

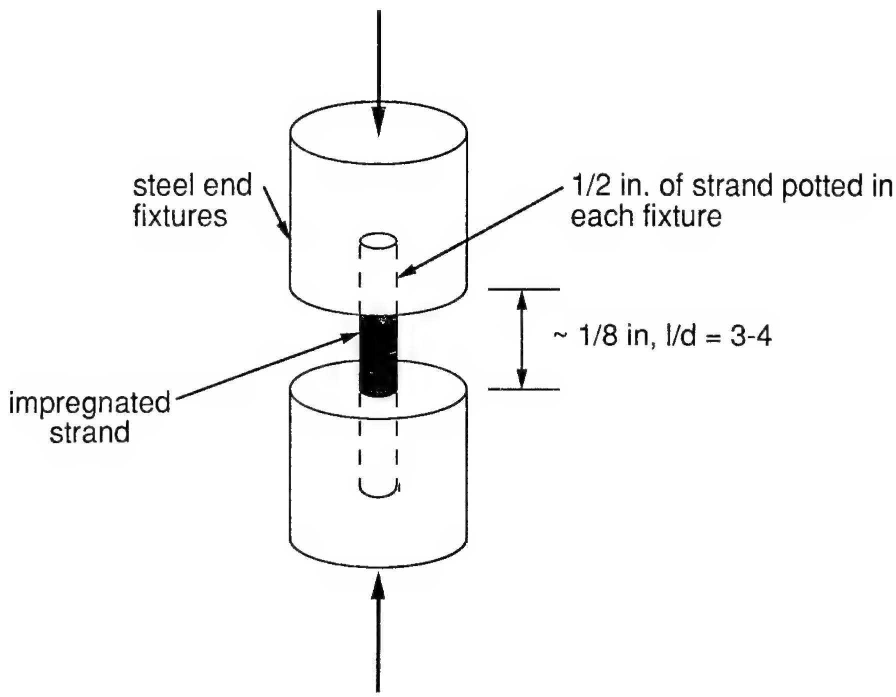
- Fiber compressive strength is not limiting factor in high tensile strength, PAN-based graphite fiber composites.
- Select composite specimen that represents material behavior:
  - eliminate imperfections (voids, fiber waviness)
  - eliminate processing variables
- Use test method that generates uniform compressive stress.

Direct Compression of Impregnated Strands

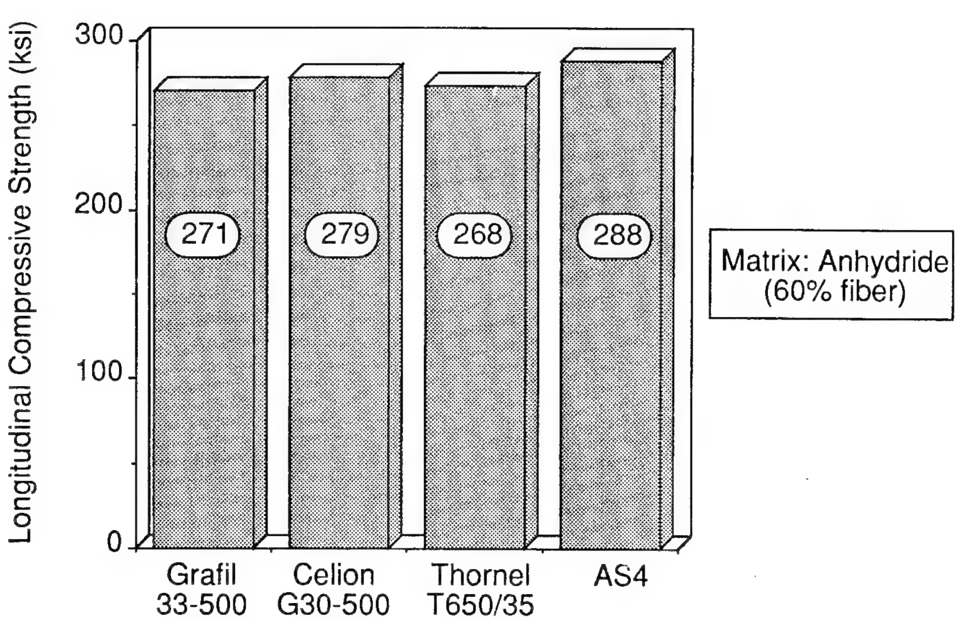
Cross-section of Impregnated 12K Graphite Fiber Strand



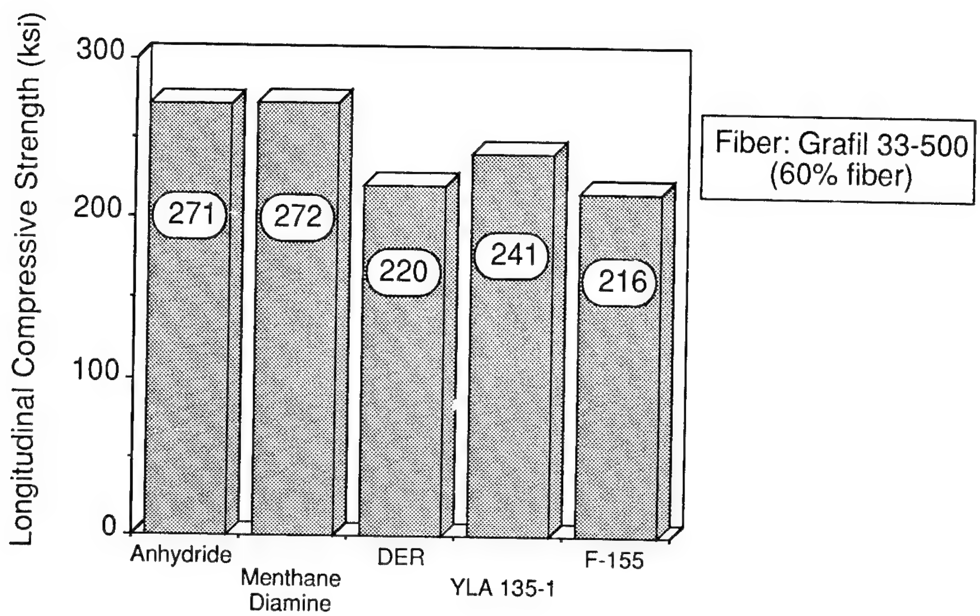
Impregnated Fiber Strand Compression



Longitudinal Compression: Effect of Fiber



Longitudinal Compression: Effect of Matrix



Summary

- Compressive failure of high tensile strength,PAN-based graphite fiber composites is not due to fiber failure.
- Material contribution to compressive failure investigated via compression of impregnated strands.
- Compressive strengths of strands higher than those typically measured for lamina.
- Preliminary results reveal sensitivity of composite compressive strength to matrix, but not to fiber.

STATIC AND DYNAMIC BEHAVIOR OF COMPOSITE HELICOPTER BLADES UNDER LARGE DEFLECTIONS

Pierre J.A. Minguet, John Dugundji

Technology Laboratory for Advanced Composites
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139

ABSTRACT

The objective of this work is to study analytically and experimentally the static and dynamic behavior of helicopter rotor blades made of composite materials. Because of their anisotropic nature, composite blades can be manufactured which exhibit some new types of behavior such as the coupling between bending and twist or between extension and twist deformations. There is a growing interest in using such effects to improve the overall performance of helicopter rotors.

A new model capable of handling arbitrarily large deflections in beams was developed. The model is based on the use of Euler angles and can take into account the structural couplings such as bending-twist and extension twist, which are introduced by the use of composite materials. A finite-differences iterative solution procedure was used to solve the resulting nonlinear equations. The model first determines the large deflection behavior of the blades under static loads, then a linearized version of the model is used to determine the small amplitude vibration behavior of the blades about their large static deflected position. Both techniques were implemented in a computer code that was fast and efficient.

A number of graphite/epoxy flat beams were manufactured with various lay-ups to demonstrate the influence of large deflections and structural couplings. In the first series of tests, the beams were cantilevered and large static deflections were measured. In the second series of tests, the natural frequencies of the beams were measured. Blades of different thicknesses which exhibit various amounts of deflection under their own weight were used, and it was found that these deflections have a strong influence on the torsion and fore-and-aft modes frequency. These effects were also observed in the analysis results, and good agreement between analysis and experiment was found for both static and dynamic results. The experiments should provide a useful set of test cases for composite, structurally coupled blades.

REFERENCES

1. Minguet, P.J.A. and Dugundji, J., "Experiments and Analysis for Structurally Coupled Composite Blades Under Large Deflections. Part 1 - Static Behavior. Part 2 - Dynamic Behavior", 30th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Mobile, Alabama, April 3-5, 1989, AIAA Papers 89-1365, 89-1366.

2. Minguet, P.J.A., "Static and Dynamic Behavior of Composite Helicopter Blades Under Large Deflections", Ph.D. Thesis, Dept. of Aeronautics and Astronautics, M.I.T., May 1989. Also, TELAC Rept. 89-7, M.I.T., May 1989.

ACKNOWLEDGEMENT

This research was supported by U.S. Army Research Office contract DAAL03-87-K-0024, with Dr. Gary Anderson as Technical Monitor.

STATIC AND DYNAMIC BEHAVIOR OF COMPOSITE HELICOPTER BLADES UNDER LARGE DEFLECTIONS

Pierre J. Minguet

John Dugundji

Technology Laboratory for Advanced Composites
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139

OBJECTIVES

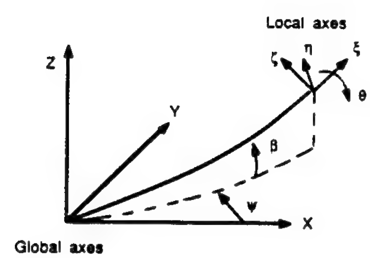
- Investigate static and dynamic behavior of structurally tailored, composite helicopter blades.
- Examine analytically effects of large static deflections, structural couplings, and initial twist.
- Provide experimental benchmark tests on composite, structurally coupled blades.

APPROACH

- Develop analytical nonlinear beam model for:
    a) Large static deflections
    b) Small vibrations about these large static deflections
- Construct composite blade models with varying structural couplings to check analyses.

LARGE DEFLECTION MODEL

Use Euler angles ψ, β, θ to describe position of deformed beam



Global axis system x, y, z fixed in space

Local axis system ξ, η, ζ fixed with beam

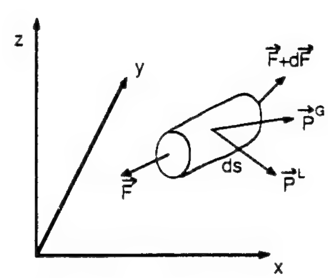
Define $[T]$ as transformation matrix from (x, y, z) to (ξ, η, ζ).

Rotations are done in order: ψ, β, θ.

$$\begin{bmatrix} i_\xi \\ i_\eta \\ i_\zeta \end{bmatrix} = [T] \begin{bmatrix} i_x \\ i_y \\ i_z \end{bmatrix}$$

$$[T] = \begin{bmatrix} \cos\beta\cos\psi & \cos\beta\sin\psi & \sin\beta \\ -\cos\theta\sin\psi - \sin\theta\sin\beta\cos\psi & +\cos\theta\cos\psi - \sin\theta\sin\beta\sin\psi & \sin\theta\cos\beta \\ +\sin\theta\sin\psi - \cos\theta\sin\beta\cos\psi & -\sin\theta\cos\psi - \cos\theta\sin\beta\sin\psi & \cos\theta\cos\beta \end{bmatrix}$$

Also, $[T]^{-1} = [T]^T$



Force equilibrium:

$$-[T]^T \vec{F} + ([T]+[dT])^T (\vec{F}+d\vec{F}) + [T]^T \vec{P}^L ds + \vec{P}^G ds = 0$$

$$\frac{d\vec{F}}{ds} - [\omega]\vec{F} + \vec{P}^L + [T]\vec{P}^G = 0$$

Moment equilibrium:

$$-[T]^T \vec{M} + ([T]+[dT])^T (\vec{M}+d\vec{M}) + [T]^T (d\vec{r} \times (\vec{F}+d\vec{F})) + [T]^T \vec{M}^L ds + \vec{M}^G ds = 0$$

$$\frac{d\vec{M}}{ds} - [\omega]\vec{M} + (\vec{t}\times\vec{F}) + \vec{M}^L + [T]\vec{M}^G = 0$$

Change in transformation matrix when moving along curve:

$$\frac{d[T]}{ds} = [\omega]\,[T]$$

with $$[\omega] = \begin{bmatrix} 0 & \omega_\zeta & -\omega_\eta \\ -\omega_\zeta & 0 & \omega_\xi \\ \omega_\eta & -\omega_\xi & 0 \end{bmatrix}$$

and ω_ξ = torsional rate
ω_η = bending curvature around η axis
ω_ζ = bending curvature around ζ axis

Obtain strain-displacement relations:

$$\omega_\xi = \frac{d\theta}{ds} + \sin\theta \frac{d\psi}{ds}$$
$$\omega_\eta = -\cos\theta \frac{d\beta}{ds} + \sin\theta \cos\beta \frac{d\psi}{ds}$$
$$\omega_\zeta = \sin\theta \frac{d\beta}{ds} + \cos\theta \cos\beta \frac{d\psi}{ds}$$

Invert relations and solve for $\frac{d\theta}{ds}$, $\frac{d\beta}{ds}$, $\frac{d\psi}{ds}$.

Generalized stress-strain relations written in terms of beam properties.

Most general form :

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \\ M_1 \\ M_2 \\ M_3 \end{bmatrix} = \begin{bmatrix} E_{11} & E_{12} & E_{13} & E_{14} & E_{15} & E_{16} \\ & E_{22} & E_{23} & E_{24} & E_{25} & E_{26} \\ & & E_{33} & E_{34} & E_{35} & E_{36} \\ & & & E_{44} & E_{45} & E_{46} \\ & \text{SYM} & & & E_{55} & E_{56} \\ & & & & & E_{66} \end{bmatrix} \begin{bmatrix} \varepsilon \\ \gamma_{\xi\eta} \\ \gamma_{\xi\zeta} \\ \omega_\xi \\ \omega_\eta \\ \omega_\zeta \end{bmatrix}$$

STATIC MODEL EQUATIONS SUMMARY

Everything considered, obtain 12 first order differential equations.

$$\frac{dF_1}{ds} - \omega_\zeta F_2 + \omega_\eta F_3 + T_{11} P_1^G + T_{12} P_2^G + T_{13} P_3^G + P_1^L = 0$$
$$\frac{dF_2}{ds} + \omega_\zeta F_1 - \omega_\xi F_3 + T_{21} P_1^G + T_{22} P_2^G + T_{23} P_3^G + P_2^L = 0$$
$$\frac{dF_3}{ds} - \omega_\eta F_1 + \omega_\xi F_2 + T_{31} P_1^G + T_{32} P_2^G + T_{33} P_3^G + P_3^L = 0$$

$$\frac{dM_1}{ds} - \omega_\zeta M_2 + \omega_\eta M_3 + T_{11} M_1^G + T_{12} M_2^G + T_{13} M_3^G + M_1^L = 0$$
$$\frac{dM_2}{ds} + \omega_\zeta M_1 - \omega_\xi M_3 + T_{21} M_1^G + T_{22} M_2^G + T_{23} M_3^G + M_2^L - F_3 = 0$$
$$\frac{dM_3}{ds} - \omega_\eta M_1 + \omega_\xi M_2 + T_{31} M_1^G + T_{32} M_2^G + T_{33} M_3^G + M_3^L + F_2 = 0$$

$$\frac{d\theta}{ds} = \omega_\xi - \sin\theta \tan\beta\, \omega_\eta - \cos\theta \tan\beta\, \omega_\zeta$$
$$\frac{d\beta}{ds} = -\cos\theta\, \omega_\eta + \sin\theta\, \omega_\zeta$$
$$\frac{d\psi}{ds} = \frac{\sin\theta}{\cos\beta}\, \omega_\eta + \frac{\cos\theta}{\cos\beta}\, \omega_\zeta$$

$$\frac{dx}{ds} = (1+\varepsilon) \cos\beta \cos\psi$$
$$\frac{dy}{ds} = (1+\varepsilon) \cos\beta \sin\psi$$
$$\frac{dz}{ds} = (1+\varepsilon) \sin\beta$$

FINITE DIFFERENCE SCHEME

Differential equations discretized with centered finite-differences formula :

$$\frac{dF_k}{ds} + G_k = 0 \qquad k = 1,2,3,\ldots$$

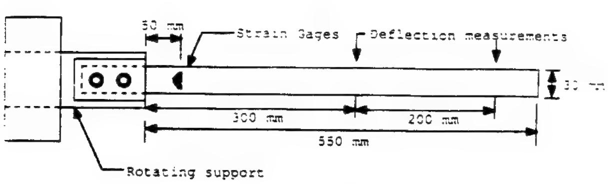
becomes

$$\frac{F_k^{i+1} - F_k^i}{\Delta s} + G_k^{i+\frac{1}{2}} = 0 \qquad k = 1,2,3,\ldots$$
$$G_k^{i+\frac{1}{2}} = \tfrac{1}{2}\left[G_k^{i+1} + G_k^i\right] \qquad i = 0, N-1$$

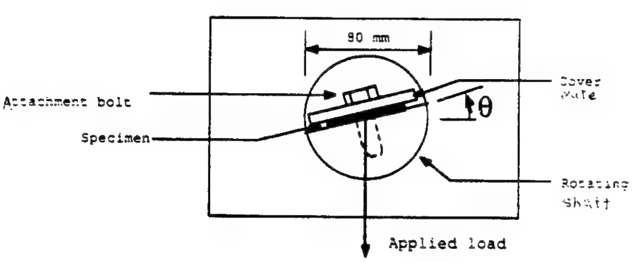
Iteration equation:

$$F_k^{i+1} = F_k^i - \tfrac{\Delta s}{2}\left[G_k^{i+1} + G_k^i\right] \qquad k = 1,2,3,\ldots \quad i = 0, N-1$$

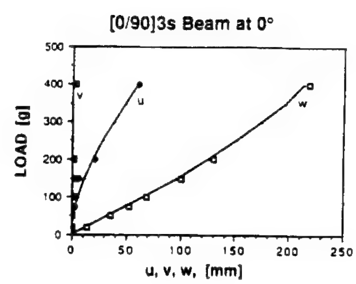
SPECIMEN CONFIGURATION

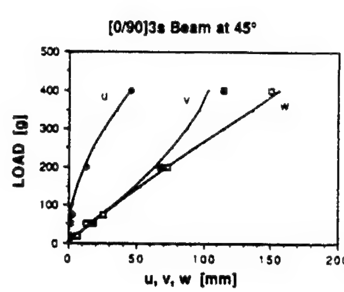


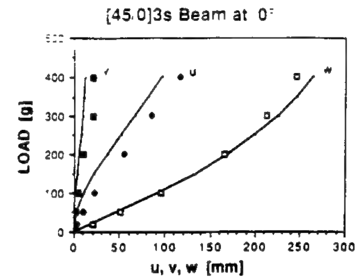
TOP VIEW

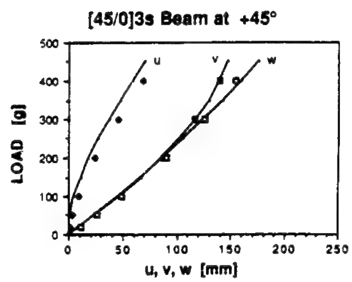


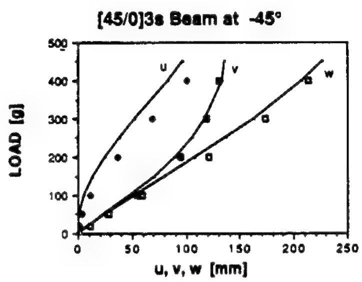
TIP VIEW











VIBRATION MODEL EQUATIONS

- Small amplitude vibrations around static position calculated by previous model.
- Linearize previous equations => replace variables with average value plus small perturbation.

  i.e., $x \rightarrow \bar{x} + x$

- Neglect squares or higher powers of perturbations. Drop terms with only "bar" quantities.

LINEARIZED EQUATIONS SUMMARY

Obtain 12 first order linear differential equas:

Force equilibrium:

$$\frac{d\mathbf{F}}{ds} + [\bar{\omega}]\,\mathbf{F} + [\omega]\,\bar{\mathbf{F}} + \mathbf{P}^L + [\bar{T}]\,\mathbf{P}^G + [T]\,\bar{\mathbf{P}}^G = 0$$

$$\frac{d\mathbf{M}}{ds} + [\bar{\omega}]\,\mathbf{M} + [\omega]\,\bar{\mathbf{M}} + \mathbf{t} \times \mathbf{F} + \mathbf{M}^L + [\bar{T}]\,\mathbf{M}^G + [T]\,\bar{\mathbf{M}}^G = 0$$

Compatibility equations:

$$\frac{d\theta}{ds} = \omega_\xi - \cos\bar{\theta}\,\tan\bar{\beta}\,\bar{\omega}_\eta\,\theta - \frac{\sin\bar{\theta}}{\cos^2\bar{\beta}}\,\bar{\omega}_\eta\,\beta - \sin\bar{\theta}\,\tan\bar{\beta}\,\omega_\eta + \sin\bar{\theta}\,\tan\bar{\beta}\,\bar{\omega}_\zeta\,\theta - \frac{\cos\bar{\theta}}{\cos^2\bar{\beta}}\,\bar{\omega}_\zeta\,\beta - \cos\bar{\theta}\,\tan\bar{\beta}\,\omega_\zeta$$

etc.

Displacements:

$$\frac{du}{ds} = -\sin\bar{\beta}\cos\bar{\psi}\,\beta - \cos\bar{\beta}\sin\bar{\psi}\,\psi$$

etc.

Linearized transformation matrix:

$$T_{11} = -\sin\bar{\beta}\cos\bar{\psi}\,\beta - \cos\bar{\beta}\sin\bar{\psi}\,\psi$$

etc.

SOLUTION PROCEDURE

- Use influence coefficient method to construct inverse of stiffness matrix:

  $$\underset{\sim}{q} = \underset{\sim}{C}\ \underset{\sim}{f}$$

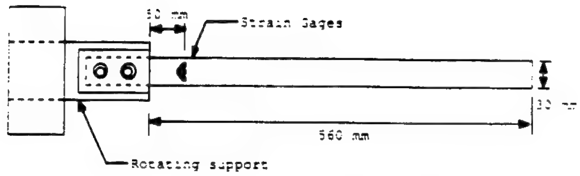
- Use finite differences to represent differential equas, divide beam into N nodes.
- Apply unit load on one d.o.f. and find displacements at all nodes.
- To find displacements, use static integration scheme.
- Use lumped mass matrix and set up st'd. eigenvalue problem:

  $$\lambda\,\underset{\sim}{x} = \underset{\sim}{M}^{1/2}\,\underset{\sim}{C}\,\underset{\sim}{M}^{1/2}\,\underset{\sim}{x}$$

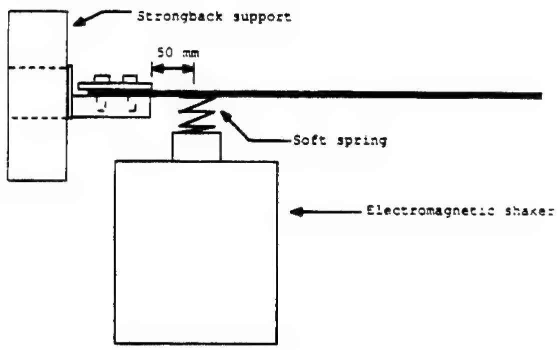
  where,

  $$\underset{\sim}{q} = \underset{\sim}{M}^{-1/2}\,\underset{\sim}{x} \quad , \qquad \lambda = 1/\omega^2$$

VIBRATION TEST SETUP



TOP VIEW



SIDE VIEW

TABLE 1 Experimentally Measured Frequencies

Laminate	W_T (mm)	1B (Hz)	2B (Hz)	3B (Hz)	1T (Hz)	1F (Hz)
$[0/90]_{3s}$	20	5.7	34	98	62	-
$[45/0]_{3s}$	18	4.3	28	78	135	-
$[20/-70_2/20]_{2a}$	12	5.8	36	103	166	-
$[0/90/0]_s$	15	3.1	19	54	89	-
	54	3.1	19	53	82	21
$[45/0/45]_s$	37	2.3	13	39	118	-
	101	2.3	13	38	101	17
$[20/-70_2/20]_a$	9	3.0	18	50	111	-
	59	3.0	18	50	117	35
$[0/90]_s$	64	2.2	13	38	54	11
	163	2.3	13	37	46	5.6
$[45/0]_s$	137	1.4	8.0	20	68	10
	202	1.4	8.2	20	57	6.5

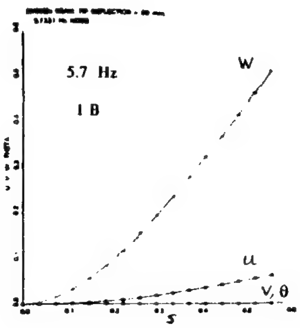
Natural Frequencies for $[0/90]_{3s}$ Beam.

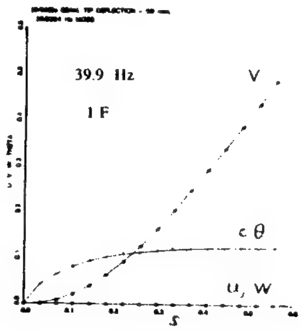
	w_T (mm)	1B (Hz)	2B (Hz)	3B (Hz)	1T (Hz)	1F (Hz)
Analysis	0	5.7	36	101	84	113
Experim.	20	5.7	34	98	62	-
Analysis	18	5.7	36	102	71	124

Natural Frequencies for $[45/0]_s$ Beam.

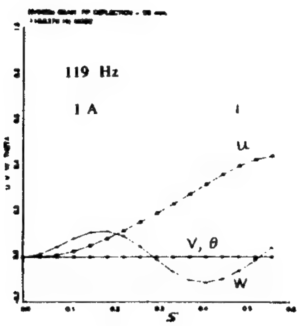
	w_T (mm)	1B (Hz)	2B (Hz)	3B (Hz)	1T (Hz)	1F (Hz)
Analysis	0	1.3	8.0	22	115	49
Experim.	137	1.4	8.0	20	68	10
Analysis	137	1.3	8.4	23	75	10
Experim.	202	1.4	8.2	20	57	6.5
Analysis	202	1.3	9.0	24	63	6.2

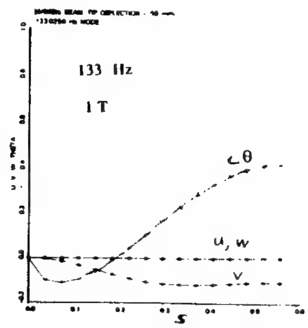
$[0/90]_{3s}$ $w_t = 59$ mm



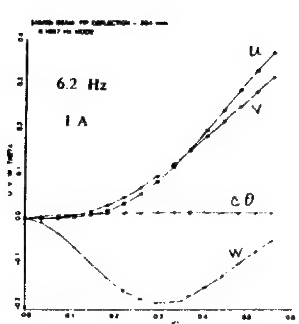


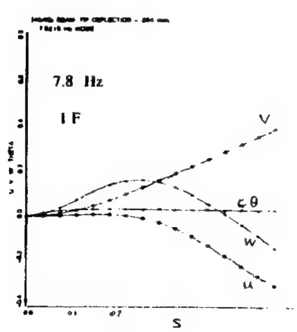
$[0/90]_{3s}$ $w_t = 59$ mm



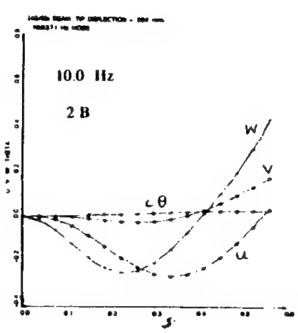


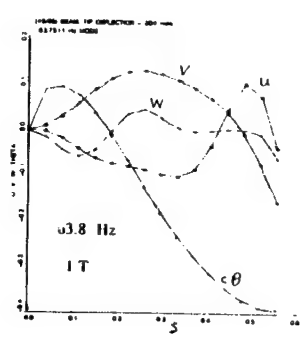
$[45/0]_s$ $w_t = 204$ mm

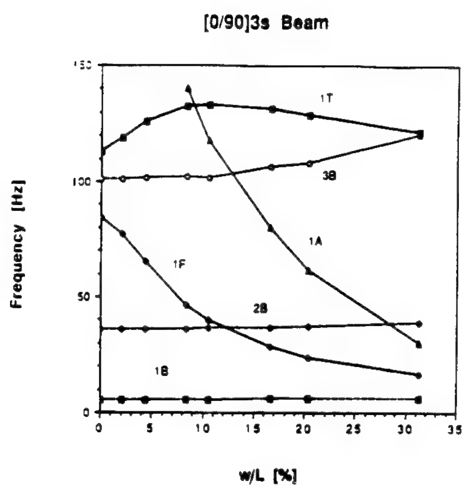


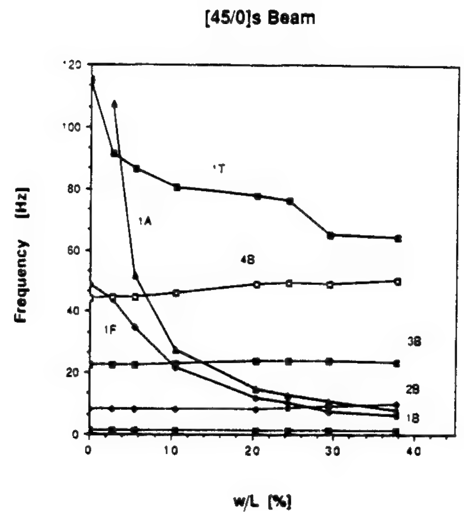


$[45/0]_s$ $w_t = 204$ mm









CONCLUSIONS

- New model for large deflections and vibrations of structurally coupled beams.
- Simple and fast solution procedure.
- Experimental static and vibration data for composite beams.
- Good agreement with experimental data.
- Strong influence of static deflections on natural frequencies and modes.

ENERGY-ABSORPTION CAPABILITY OF COMPOSITE TUBES AND BEAMS

Gary L. Farley

Aerostructures Directorate
US Army Aviation Research and Technology Activity
AVSCOM
Langley Research Center

ABSTRACT

In this study, the objective was to develop a method of predicting the energy-absorption capability of composite subfloor beam structures. Before it is possible to develop such an analysis capability, an in-depth understanding of the crushing process of composite materials must be achieved. Many variables affect the crushing process of composite structures, such as the constituent materials' mechanical properties, specimen geometry, and crushing speed. A comprehensive experimental evaluation of tube specimens was conducted to develop insight into how composite structural elements crush and what are the controlling mechanisms.

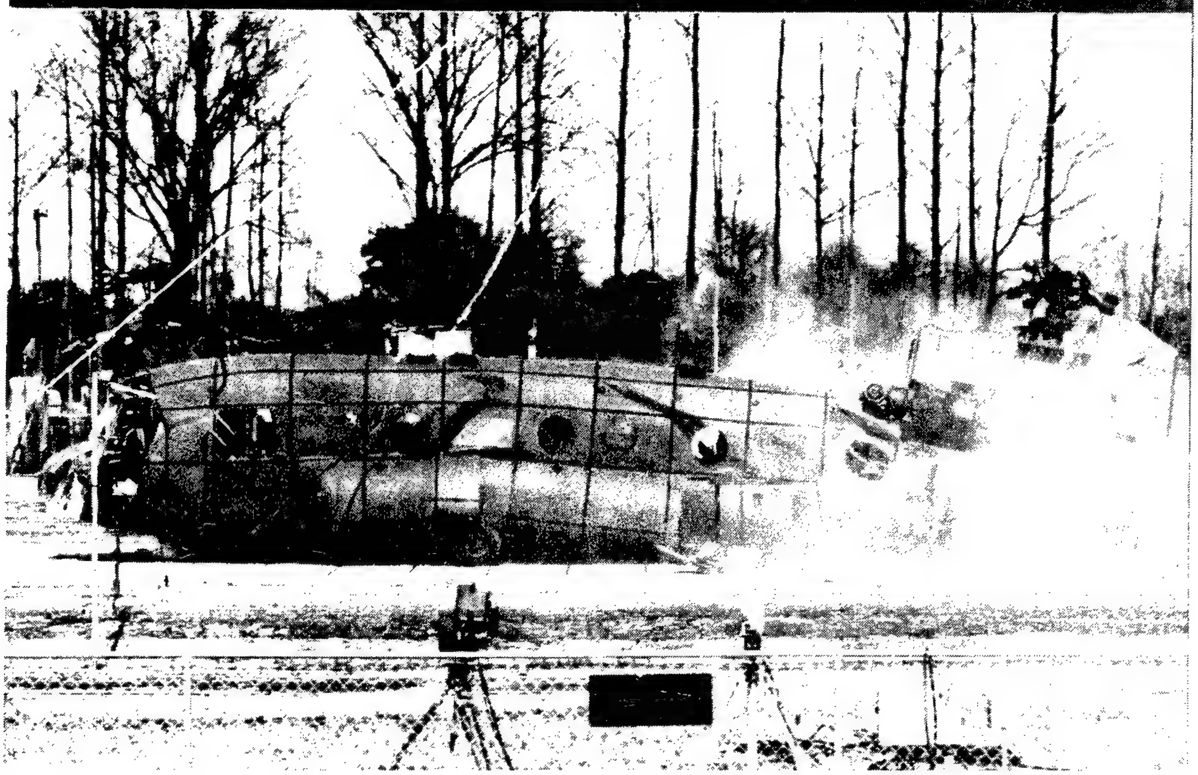
In this study, the four characteristic crushing modes, transverse shearing, brittle fracturing, lamina bending, and local buckling were identified and the mechanisms that control the crushing process defined. An in-depth understanding was developed of how material properties affect energy-absorption capability. For example, an increase in fiber and matrix stiffness and failure strain can, depending upon the configuration of the tube, increase energy-absorption capability. An analysis to predict the energy-absorption capability of composite tube specimens was developed and verified. Good agreement between experiment and prediction was obtained.

Sine-wave and integrally stiffened composite beams were evaluated. Composite energy-absorbing beams crush in modes similar to tubular specimens that are made from the same material and have similar geometry. Energy-absorption trends of the composite beams are similar to energy-absorption trends from the composite tube specimens. Composite beams are equal or superior energy absorbers to comparable geometry metallic beams. Finally, a simple and accurate method of predicting the energy-absorption capability of composite beams was developed. This analysis is based upon the energy-absorption capability of the beams' constituent elements.

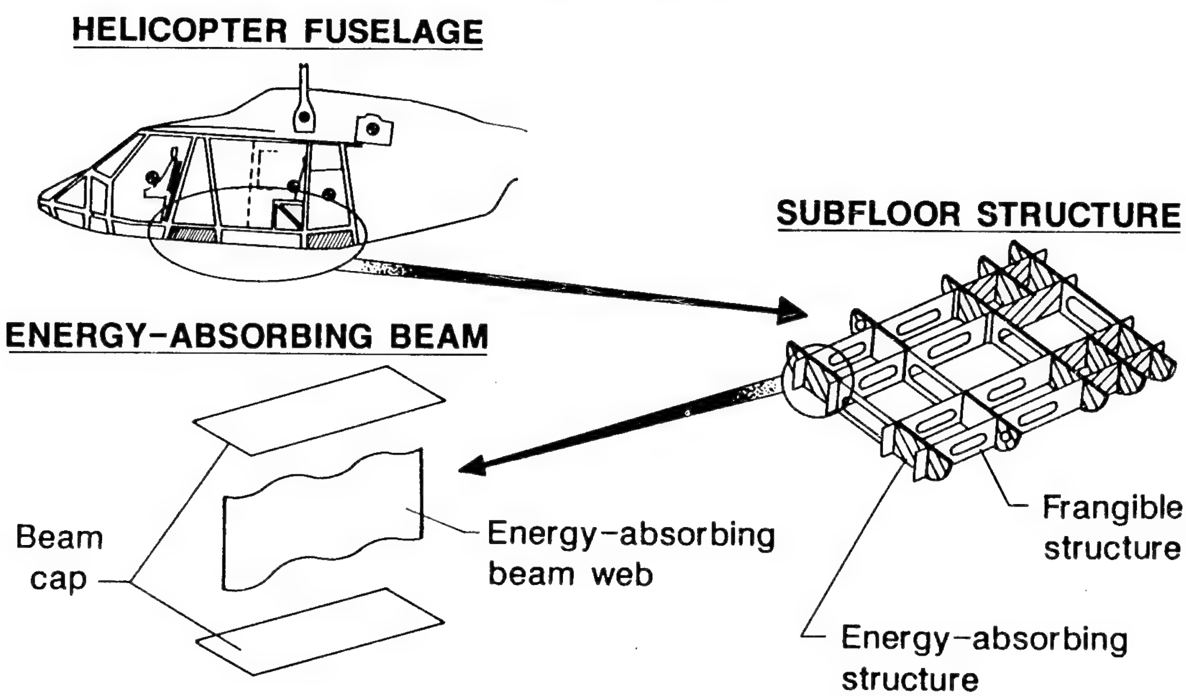
REFERENCE

1. G. L. Farley and R. M. Jones, "Energy-Absorption Capability of Composite Tubes and Beams," NASA TM 101634 and AVSCOM TR 89-B-003, July 1989.

CRASH TEST OF CH-47 HELICOPTER



ENERGY-ABSORBING HELICOPTER SUBFLOOR STRUCTURE



SCOPE OF PRESENTATION

Test specimens, test equipment, and procedures

Material and structural characterization of tube specimens

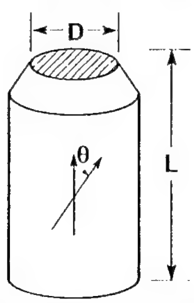
- Crushing modes and mechanisms
- Effect of fiber and material mechanical properties
- Effect of tube structural variables
- Effect of crushing speed
- Tube analysis

Material and structural characterization of subfloor beam specimens

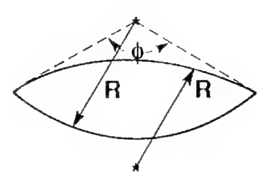
- Effect of beam geometry
- Crushing modes
- Beam analysis

Summary of results

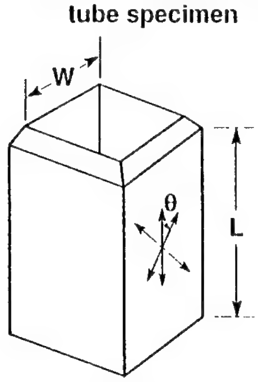
TYPICAL TUBULAR TEST SPECIMENS



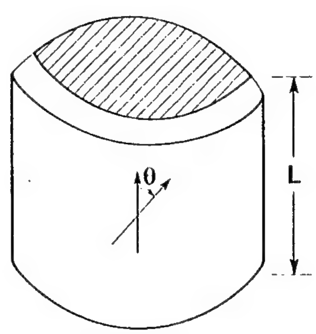
Circular cross-section
tube specimen



Top view of near-elliptical tube



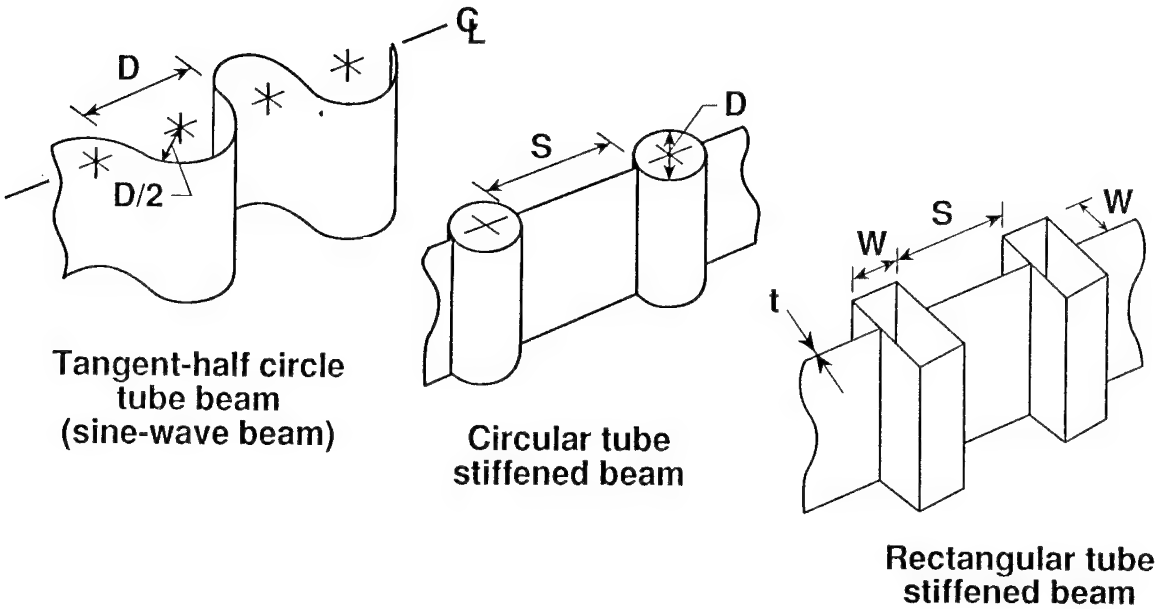
Square cross-section
tube specimen



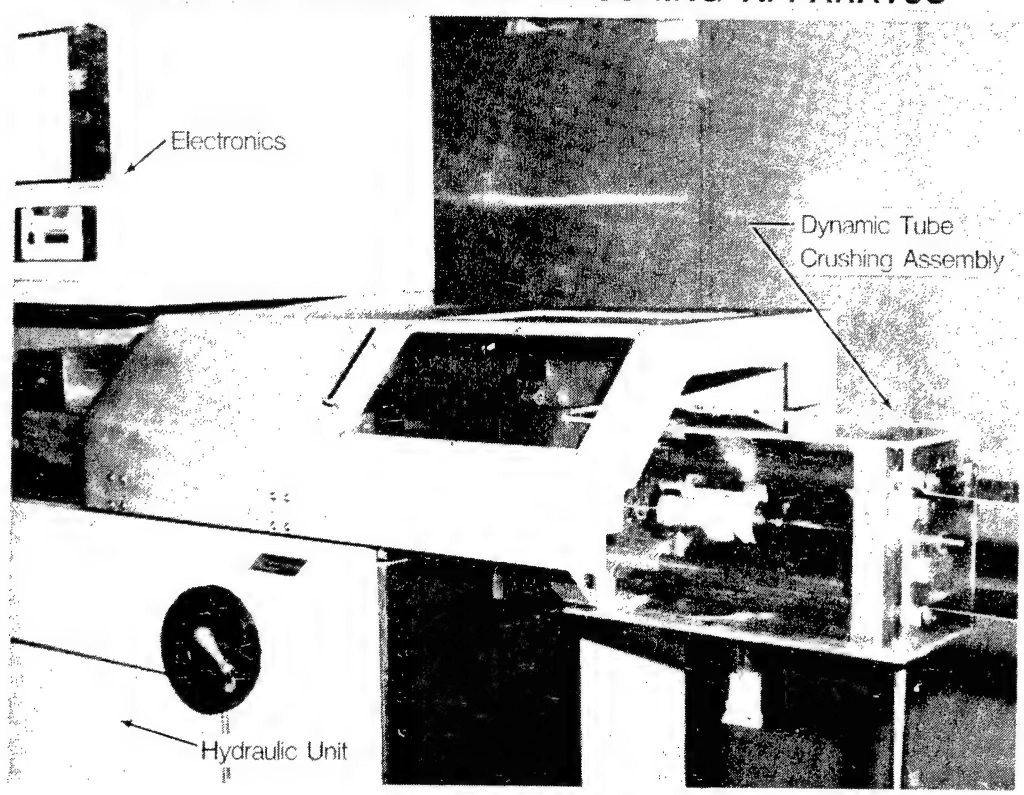
Near-elliptical cross-section
tube specimen

ENERGY-ABSORBING BEAM CONCEPTS

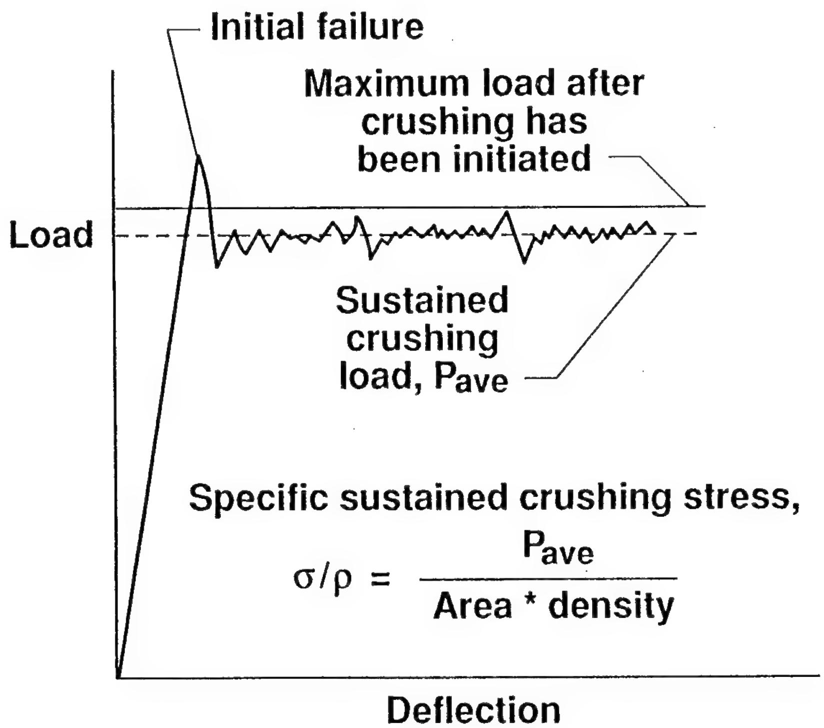
Typical beam web construction

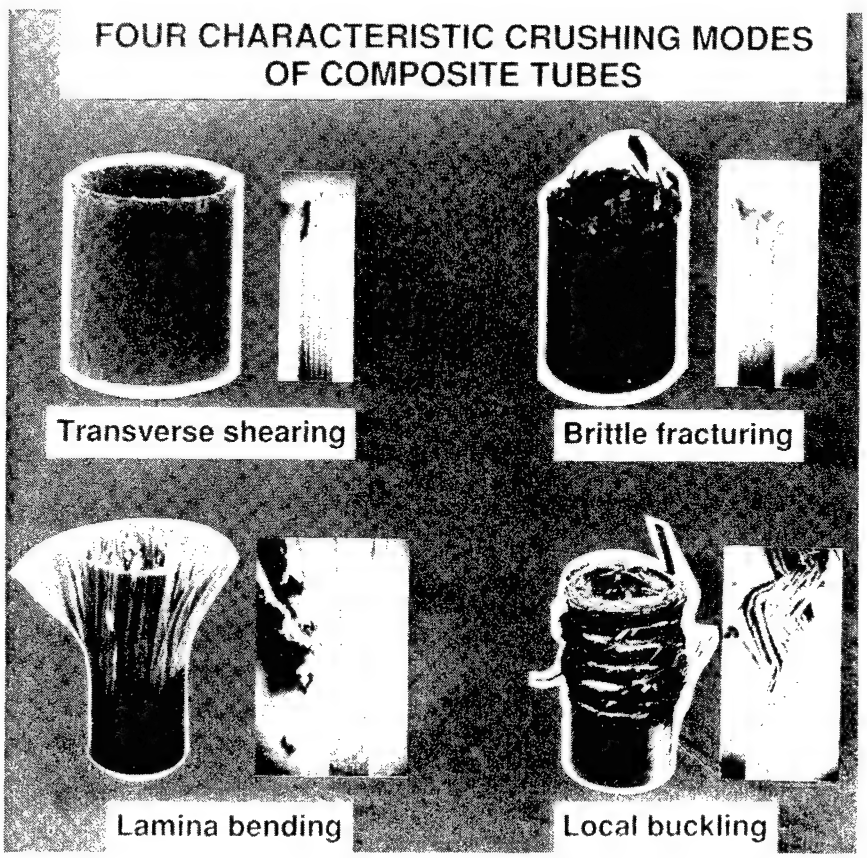


CONSTANT SPEED TUBE CRUSHING APPARATUS

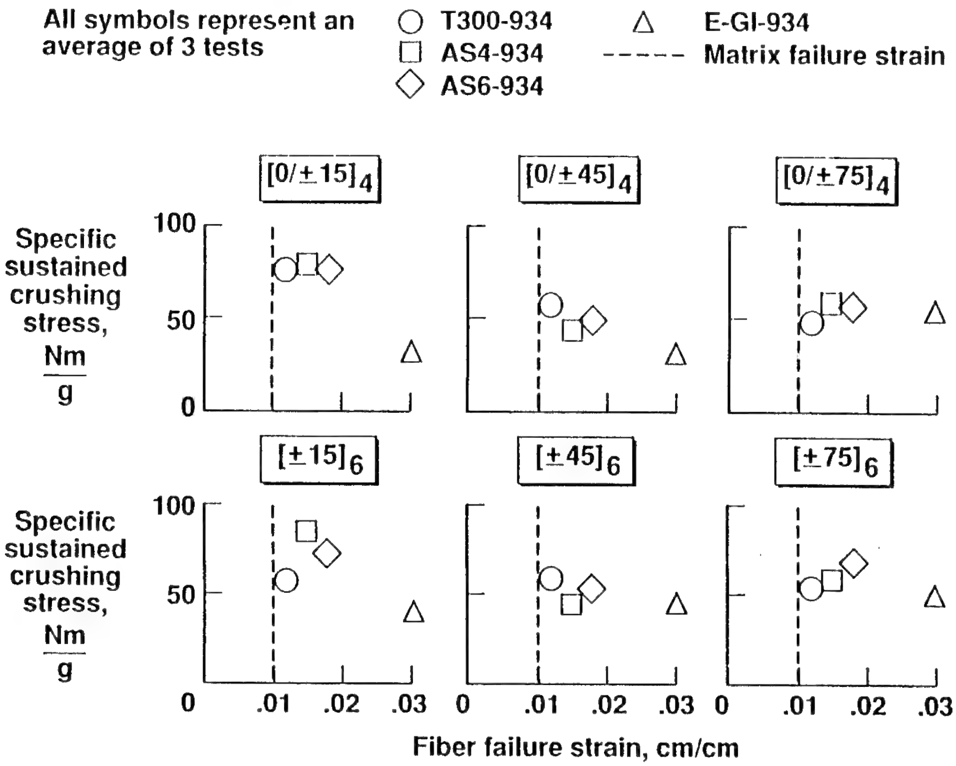


SCHEMATIC OF LOAD-DEFLECTION CURVE OF COMPOSITE TUBE SPECIMEN

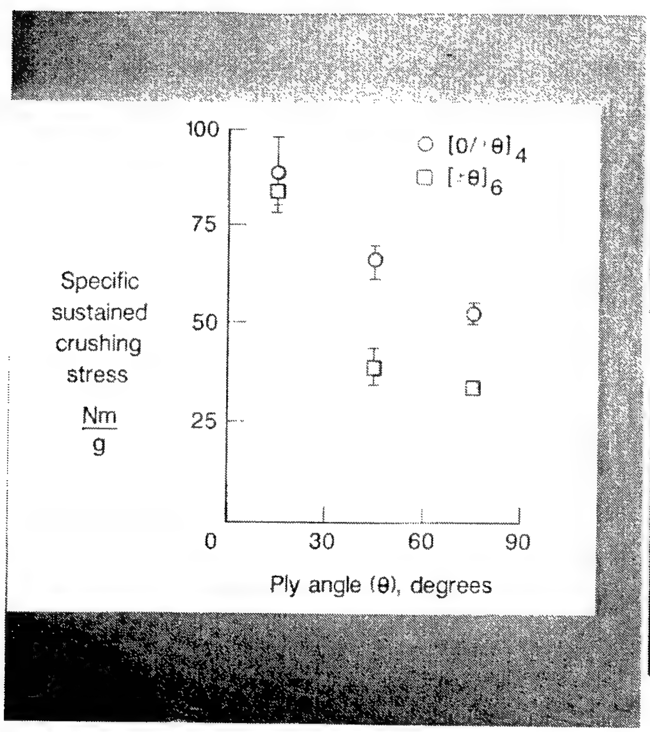




EFFECT OF FIBER FAILURE STRAIN ON ENERGY-ABSORPTION CAPABILITY



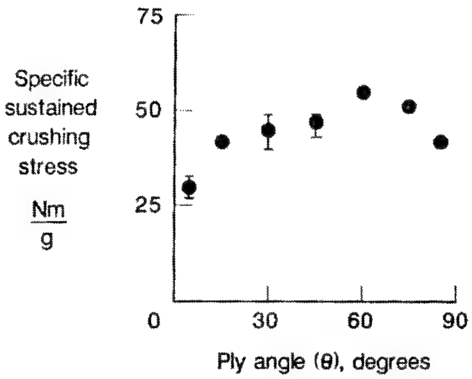
ENERGY-ABSORPTION CAPABILITY OF $[0/\pm\Theta]_4$ AND $[\pm\Theta]_6$ E-Gl-HX205 COMPOSITE TUBES

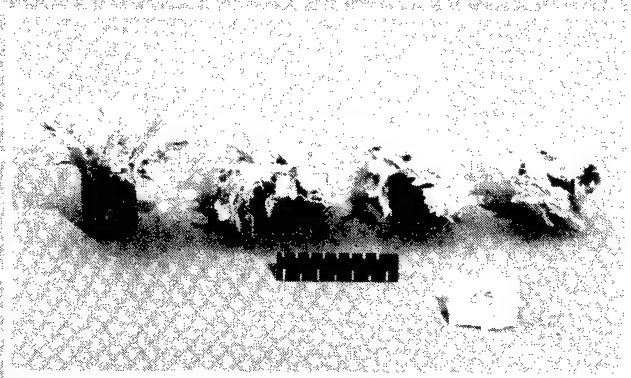


[0/±15]$_4$ [0/±45]$_4$ [0/±75]$_4$

[±15]$_6$ [±45]$_6$ [±75]$_6$

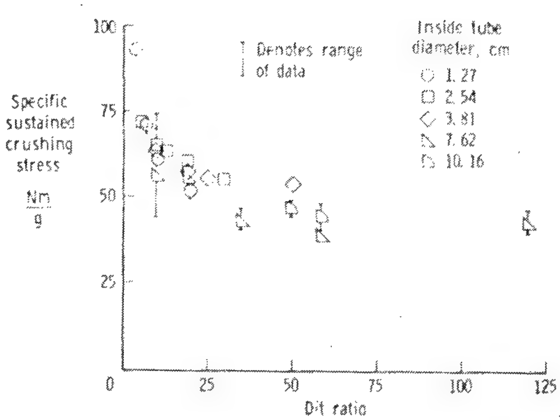
ENERGY-ABSORPTION CAPABILITY OF $[\pm\theta]_6$ E-Gl/934 COMPOSITE TUBES



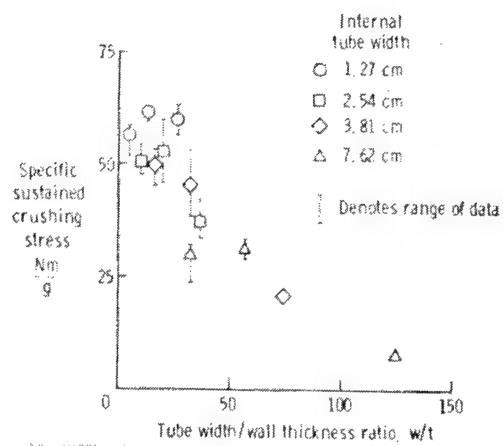


$[\pm15]_6$ $[\pm30]_6$ $[\pm45]_6$ $[\pm60]_6$

INFLUENCE OF SPECIMEN GEOMETRY ON ENERGY-ABSORPTION CAPABILITY OF Gr-Ep $[\pm45]_N$ TUBES

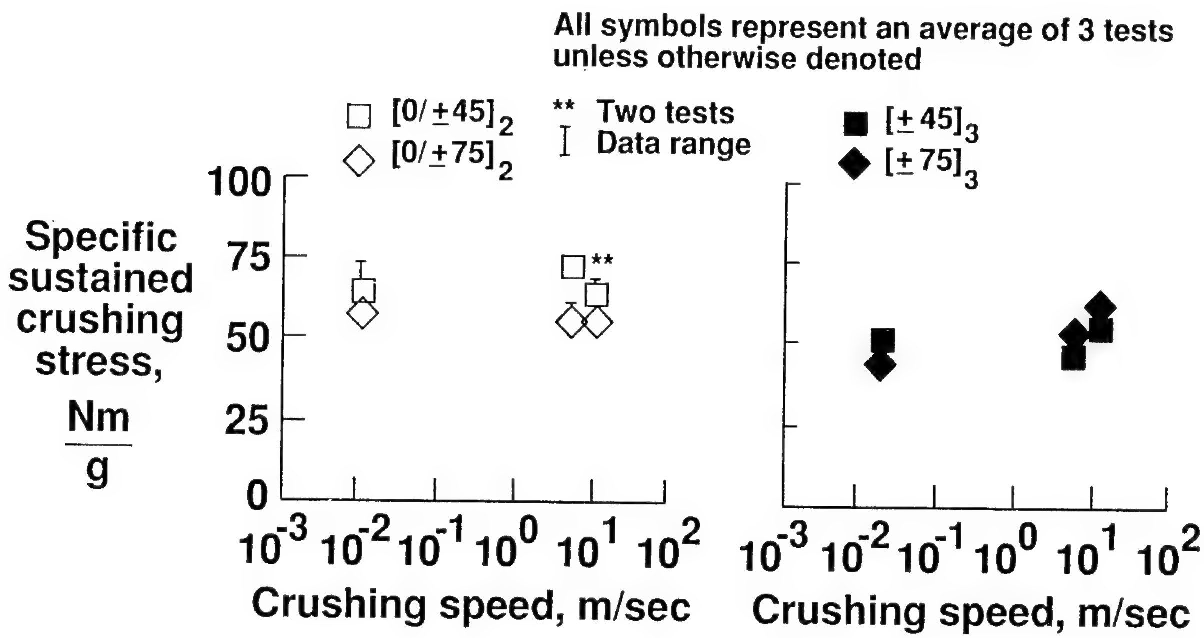


Circular cross section tubes

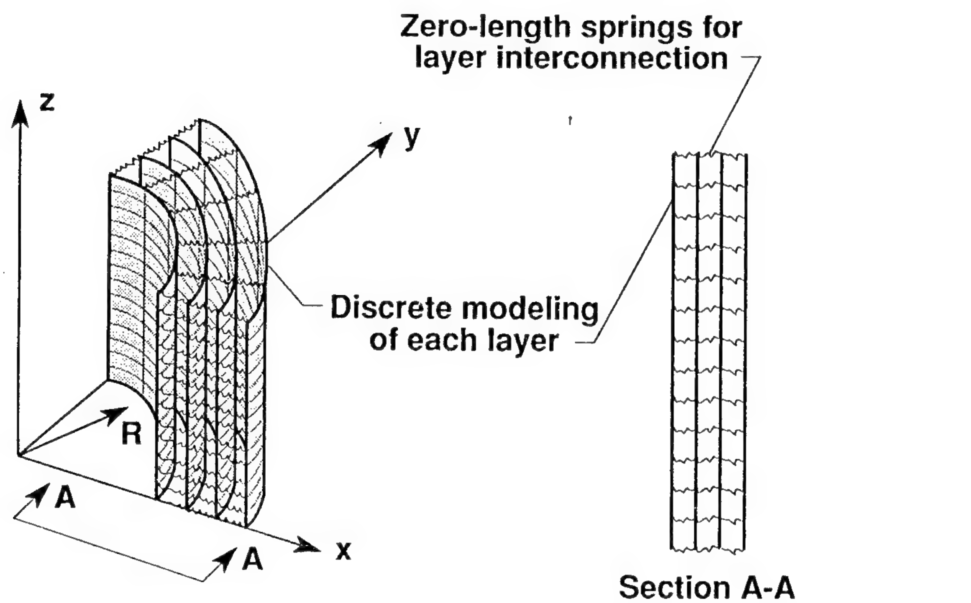


Square cross section tubes

EFFECTS OF CRUSHING SPEED ON Gr-Ep TUBES

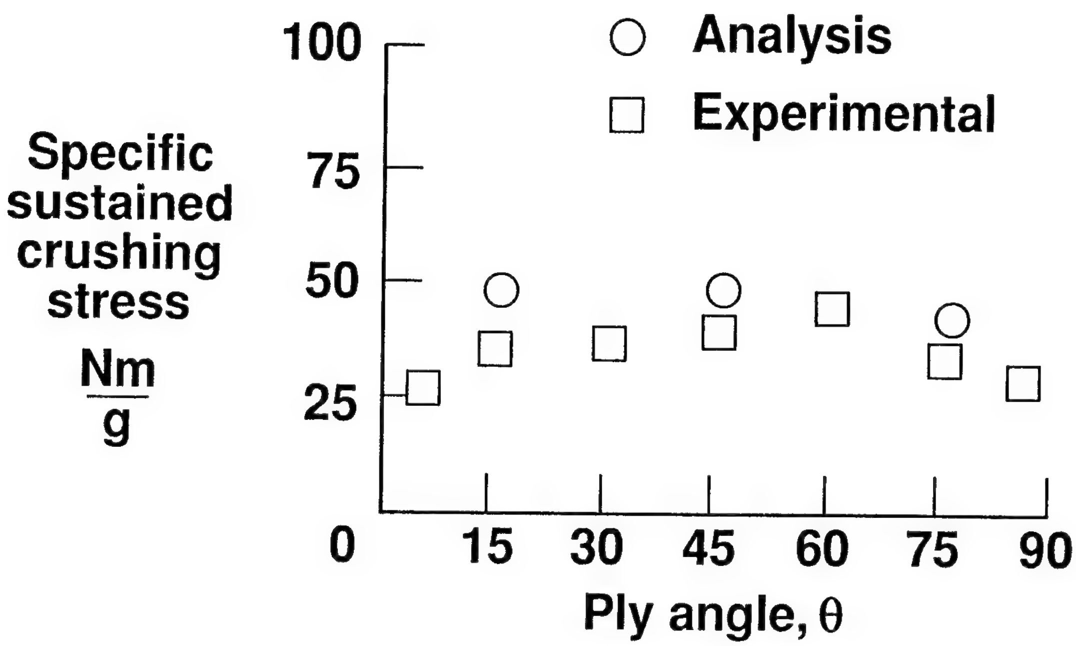


FINITE ELEMENT MODEL

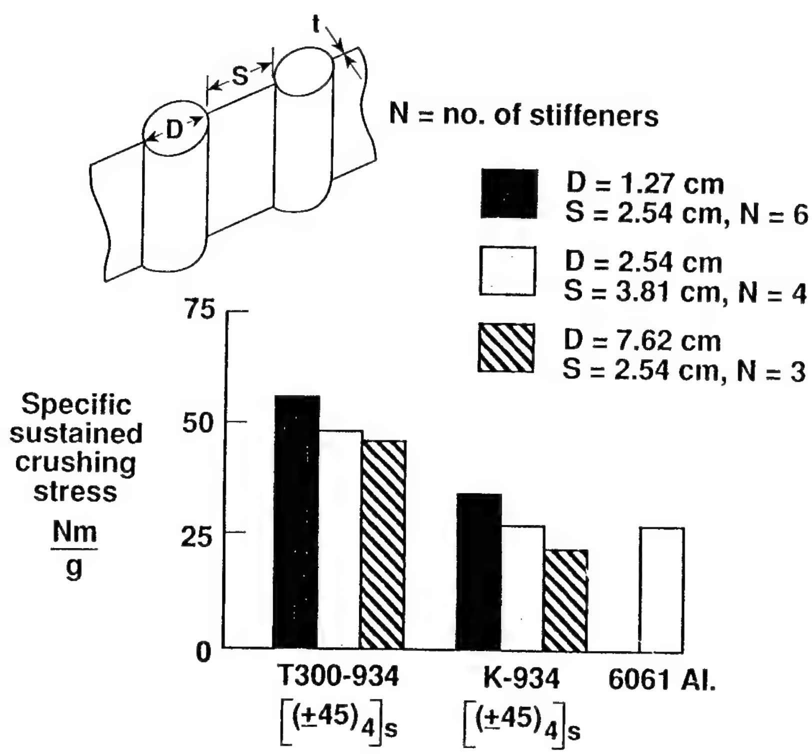


Zero-length springs have 3 axial and 3 rotational stiffness components

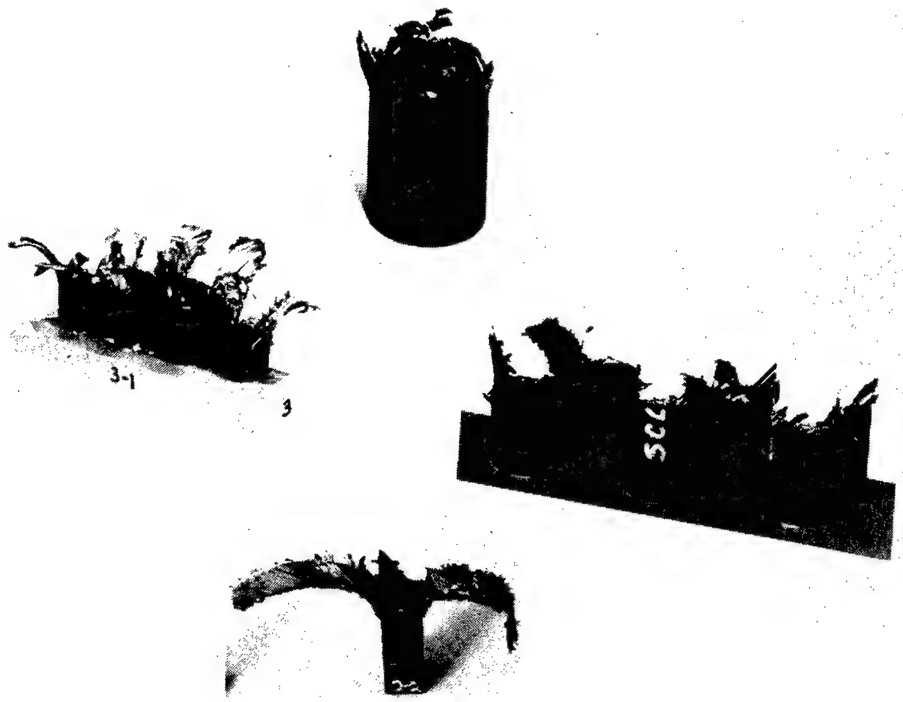
COMPARISON OF PREDICTED AND EXPERIMENTAL ENERGY-ABSORPTION CAPABILITY OF [±Θ] KEVLAR-EPOXY TUBES



ENERGY-ABSORPTION CAPABILITY OF CIRCULAR TUBE STIFFENED BEAMS



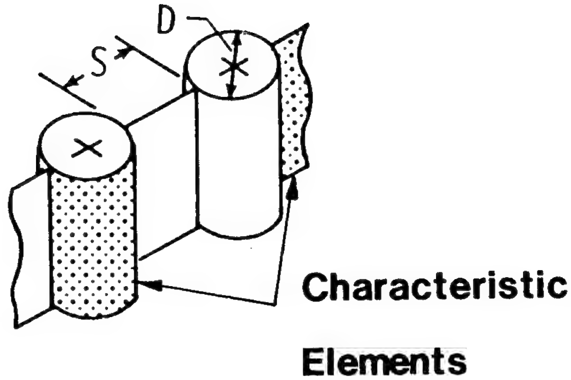
SIMILARITY IN CRUSHING MODES OF Gr-Ep TUBES AND SUBFLOOR BEAMS



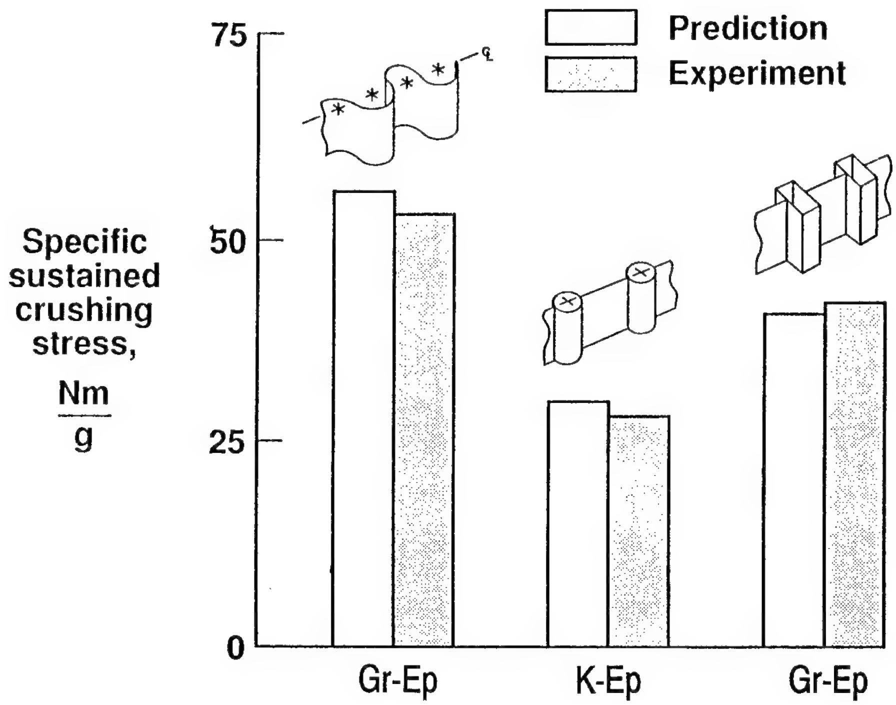
SUBFLOOR BEAM ENERGY ABSORPTION PREDICTION METHOD

Hypothesis

$$(\sigma/\rho)_{S.E.} = \sum_{i=1}^{N} \frac{A_{i_{C.E}}}{A_{S.E.}} * (\sigma/\rho)_{i_{C.E.}}$$



ENERGY-ABSORPTION CAPABILITY OF COMPOSITE BEAMS



SUMMARY OF RESULTS

Identified the four characteristic crushing modes and the mechanisms that control the crushing process.

Developed an in-depth understanding of how the different material properties, structural variables, and loading conditions affect the crushing process.

A "first generation" analysis was developed to predict the crushing response of composite tubes.

Crushing response of composite beams follows the same trends as tube specimens.

Composite beams have been found to be equal or superior energy absorbers to aluminum beams.

A simple, yet accurate, analysis was developed to predict the energy-absorption capability of composite beams.

A THREE-DIMENSIONAL CONSTITUTIVE THEORY
FOR FIBER COMPOSITE LAMINATES*

Richard M. Christensen

Department of Applied Science
University of California, Davis
and
Lawrence Livermore National Laboratory

and

Edward Zywicz
Lawrence Livermore National Laboratory
Livermore, CA 94550

ABSTRACT

A three-dimensional elastic constitutive theory is developed for application to fiber composite laminated media. The lamina level constitutive relationship is a specific subset of general transversely-isotropic media behavior. This special class of lamina behavior permits the development of an exact lamination procedure for systems assembled from a single lamina type. The three-dimensional constitutive form for the laminate is determined in terms of the sub-scale lamina properties and the orientations of each lamina. The extension of this specific constitutive relationship to general transfersely-isotropic lamina involves separation of the five lamina-scale properties into fiber-dominated versus matrix-dominated classifications and the development of a generalized averaging procedure for the matrix-dominated properties. The resulting three-dimensional constitutive/lamination theory is evaluated through comparisons between exact solutions, using data bases appropriate for graphite and glass epoxy systems in quasi-isotropic lay-ups. The theory remains highly effective through the transition from thin laminate to thick laminate behavior and even beyond that through the transition from thick laminate behavior to fully and strongly three-dimensional elastic behavior. The generalized averaging procedure for the matrix-dominated properties produces variations in results that are the same or less than the variations in results due to the experimental uncertainty in the matrix-dominated properties themselves. The theory is fairly simple and extremely versatile in its application.

*Work performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

ANALYSIS OF THICK COMPOSITE LAMINATES

C. T. Sun

School of Aeronautics and Astronautics
Purdue University
West Lafayette, Indiana 47907

ABSTRACT

Classical laminated plate theory provides an efficient way to analyze thin composite laminates. For moderately thick laminates, high order plate theories are often employed to improve accuracy. These high order theories are usually more involved mathematically. Moreover, they are also limited by their 2-dimensional nature and cannot be used to account for 3-dimensional characteristics.

In actual applications of thick laminates, a certain periodic stacking sequence must be maintained in order to avoid warping due to the presence of curing stresses. If the characteristic length of deformation of the global composite is large compared with the periodicity, then the nonhomogeneous properties over each typical cell may be smeared out and effective properties used. Thus, all the cells are represented by the same anisotropic medium, and, consequently, the whole laminate can be effectively represented by a homogeneous anisotropic solid.

In this paper, thick laminates consisting of large numbers of a repeating sublaminate (the typical cell) are considered. The thickness of the typical sublaminate is assumed to be small as compared with the total laminate thickness, and the laminate is modeled as a three-dimensional homogeneous anisotropic solid whose effective moduli are derived from a representative volume -- the typical sublaminate. The sublaminate is evaluated using constant stress and constant strain assumptions for its six independent modes of deformation. Explicit expressions for the three-dimensional effective moduli are then obtained from this exercise. For balanced laminates of a single composite system, reduced expressions for these effective moduli are also derived.

The effective modulus model is used to perform stress analysis for a number of problems involving thick-section laminates. These problems include thick laminates subjected to pressure applied in a small area, laminates containing cracks, and thermal stresses in laminated cylinders. A global-local procedure is introduced to recover actual stresses in the lamina from the effective modulus model.

ANALYSIS OF THICK COMPOSITE LAMINATES*

C. T. SUN

SCHOOL OF AERONAUTICS AND ASTRONAUTICS
PURDUE UNIVERSITY

*This work was supported by ONR under Contract No. N00014-84-K-0554 with Purdue University. Dr. Y. Rajapakse was the technical monitor.

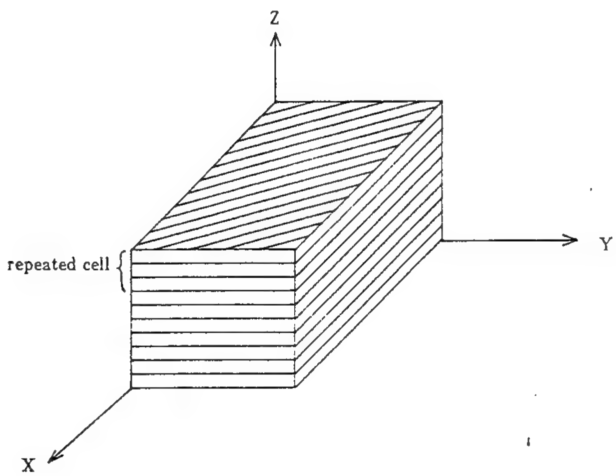
OBJECTIVE

TO DEVELOP AN EFFICIENT METHOD FOR ANALYZING THICK-SECTION COMPOSITE LAMINATES WITH OR WITHOUT DELAMINATION CRACKS

APPROACH

- DEVELOP A 3-D EFFECTIVE MODULUS MODEL FOR THICK-SECTION COMPOSITE LAMINATES
- DEVELOP A GLOBAL-LOCAL METHOD FOR RECOVERING LOCAL STRESSES IN A LAMINA
- EMPLOY CRACK CLOSURE TECHNIQUE TO CALCULATE STRAIN ENERGY RELEASE RATE FOR DELAMINATION CRACKS

THICK LAMINATE WITH REPETITIVE CELLS



3-D EFFECTIVE MODULI

Basic Assumptions

- **A typical sublaminate exists.**
- **In the sublaminate, either Voigt or Reuss assumption is valid; i.e.,**

$$\varepsilon_{xx}^{(k)} = \bar{\varepsilon}_{xx} \quad , \quad \varepsilon_{yy}^{(k)} = \bar{\varepsilon}_{yy} \quad , \quad \gamma_{xy}^{(k)} = \bar{\gamma}_{xy}$$

$$\sigma_{zz}^{(k)} = \bar{\sigma}_{zz} \quad , \quad \sigma_{yz}^{(k)} = \bar{\sigma}_{yz} \quad , \quad \sigma_{xz}^{(k)} = \bar{\sigma}_{xz}$$

$$\bar{\sigma}_{ij} = \frac{1}{V} \int_V \sigma_{ij}\, dV \quad , \quad \bar{\varepsilon}_{ij} = \frac{1}{V} \int_V \varepsilon_{ij}\, dV$$

Effective Elastic Constants

$$\{\bar{\sigma}\} = [\bar{c}]\{\bar{\varepsilon}\}$$

$$\bar{c}_{11} = \sum_{k=1}^{N} v_k c_{11}^{(k)} + \sum_{k=2}^{N} \left[c_{13}^{(k)} - \lambda_{13}\right] v_k \left[c_{13}^{(1)} - c_{13}^{(k)}\right] / c_{33}^{(k)}$$

$$\bar{c}_{33} = 1 / \left[\sum_{k=1}^{N} v_k / c_{33}^{(k)}\right]$$

$$\bar{c}_{12} = \sum_{k=1}^{N} v_k c_{12}^{(k)} + \sum_{k=2}^{N} \left[c_{13}^{(k)} - \lambda_{13}\right] v_k \left[c_{23}^{(1)} - c_{23}^{(k)}\right] / c_{33}^{(k)}$$

$$\bar{c}_{16} = \sum_{k=1}^{N} v_k c_{16}^{(k)} + \sum_{k=2}^{N} (c_{13}^{(k)} - \lambda_{13})\, v_k \left[c_{36}^{(1)} - c_{36}^{(k)}\right] / c_{33}^{(k)}$$

$$\bar{c}_{13} = \sum_{k=1}^{N} v_k c_{13}^{(k)} + \sum_{k=2}^{N} \left[c_{33}^{(k)} - \lambda_{33}\right] v_k \left[c_{13}^{(1)} - c_{13}^{(k)}\right] / c_{33}^{(k)}$$

$$\bar{c}_{26} = \sum_{k=1}^{N} v_k c_{26}^{(k)} + \sum_{k=2}^{N} \left[c_{23}^{(k)} - \lambda_{23}\right] v_k \left[c_{36}^{(1)} - c_{36}^{(k)}\right] / c_{33}^{(k)}$$

$$\bar{c}_{22} = \sum_{k=1}^{N} v_k c_{22}^{(k)} + \sum_{k=2}^{N} \left[c_{23}^{(k)} - \lambda_{23}\right] v_k \left[c_{23}^{(1)} - c_{23}^{(k)}\right] / c_{33}^{(k)}$$

$$\bar{c}_{36} = \sum_{k=1}^{N} v_k c_{36}^{(k)} + \sum_{k=2}^{N} \left[c_{33}^{(k)} - \lambda_{33}\right] v_k \left[c_{36}^{(1)} - c_{36}^{(k)}\right] / c_{33}^{(k)}$$

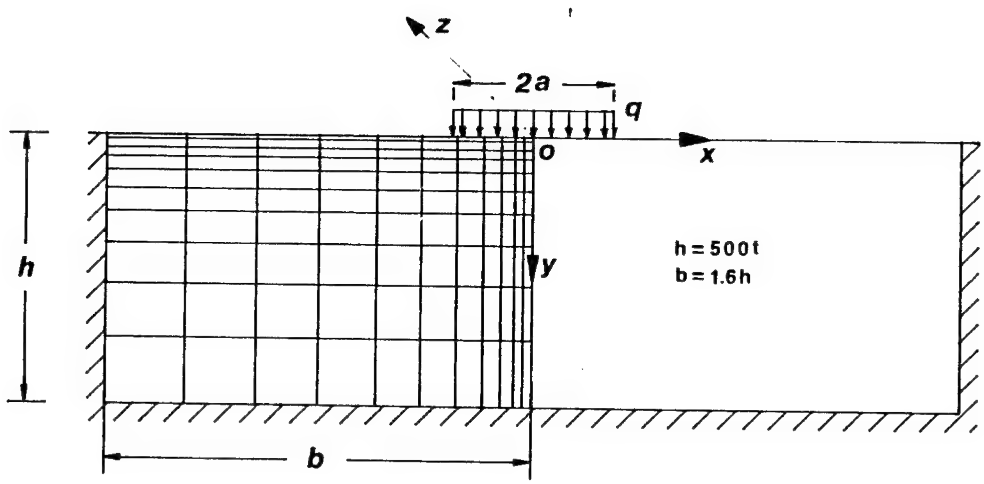
$$\bar{c}_{23} = \sum_{k=1}^{N} v_k c_{23}^{(k)} + \sum_{k=2}^{N} \left[c_{33}^{(k)} - \lambda_{33}\right] v_k \left[c_{23}^{(1)} - c_{23}^{(k)}\right] / c_{33}^{(k)}$$

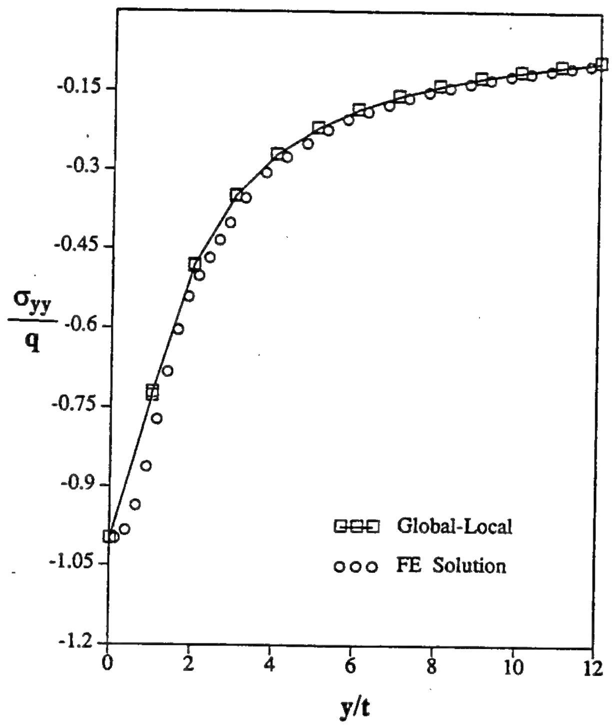
LAMINA STRESSES

$$\begin{Bmatrix} \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{xz} \end{Bmatrix}_k = \begin{Bmatrix} \bar{\sigma}_{zz} \\ \bar{\sigma}_{yz} \\ \bar{\sigma}_{xz} \end{Bmatrix} = \begin{bmatrix} c_{31} & c_{32} & c_{36} \\ c_{41} & c_{42} & c_{46} \\ c_{51} & c_{52} & c_{56} \end{bmatrix}_k \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{Bmatrix}_k + \begin{bmatrix} c_{33} & c_{34} & c_{35} \\ c_{43} & c_{44} & c_{45} \\ c_{53} & c_{45} & c_{55} \end{bmatrix}_k \begin{Bmatrix} \varepsilon_{zz} \\ \varepsilon_{yz} \\ \gamma_{xz} \end{Bmatrix}_k$$

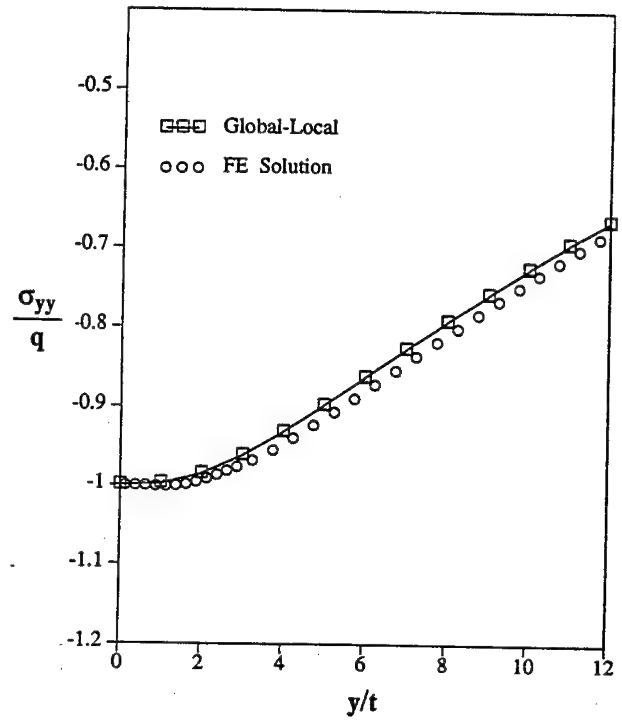
$$\begin{Bmatrix} \varepsilon_{zz} \\ \varepsilon_{yz} \\ \gamma_{xz} \end{Bmatrix}_k = \begin{bmatrix} c_{33} & c_{34} & c_{35} \\ c_{43} & c_{44} & c_{45} \\ c_{53} & c_{45} & c_{55} \end{bmatrix}_k^{-1} \left\{ \begin{Bmatrix} \bar{\sigma}_{zz} \\ \bar{\sigma}_{yz} \\ \bar{\sigma}_{xz} \end{Bmatrix} - \begin{bmatrix} c_{31} & c_{32} & c_{36} \\ c_{41} & c_{42} & c_{46} \\ c_{51} & c_{52} & c_{56} \end{bmatrix}_k \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{Bmatrix}_k \right\}$$

$$\begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xy} \end{Bmatrix}_k = \begin{Bmatrix} \bar{\varepsilon}_{xx} \\ \bar{\varepsilon}_{yy} \\ \bar{\gamma}_{xy} \end{Bmatrix}$$

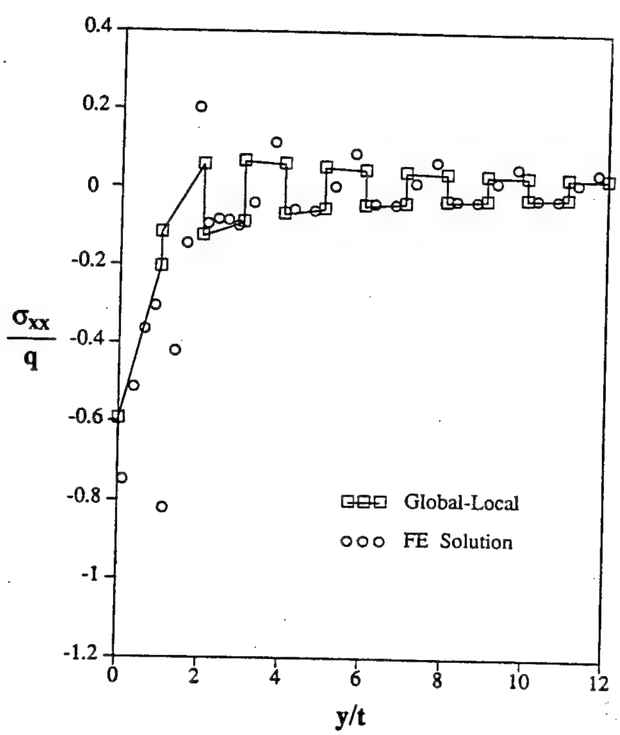




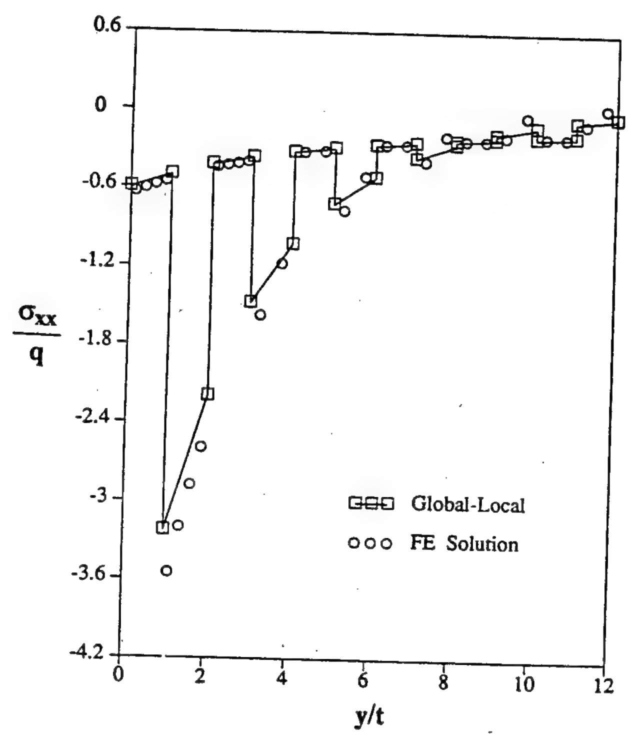
Distribution of σ_{yy}/q along $x/t = 0.05$ in the $[0/90]_{250}$ laminate for $a/t = 1$.



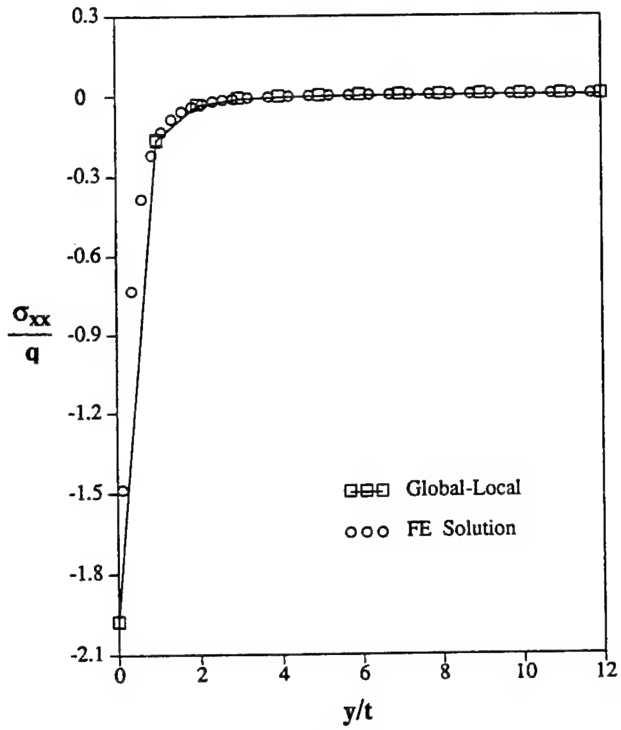
Distribution of σ_{yy}/q along $x/t = 0.05$ in the $[0/90]_{250}$ laminate for $a/t = 10$.



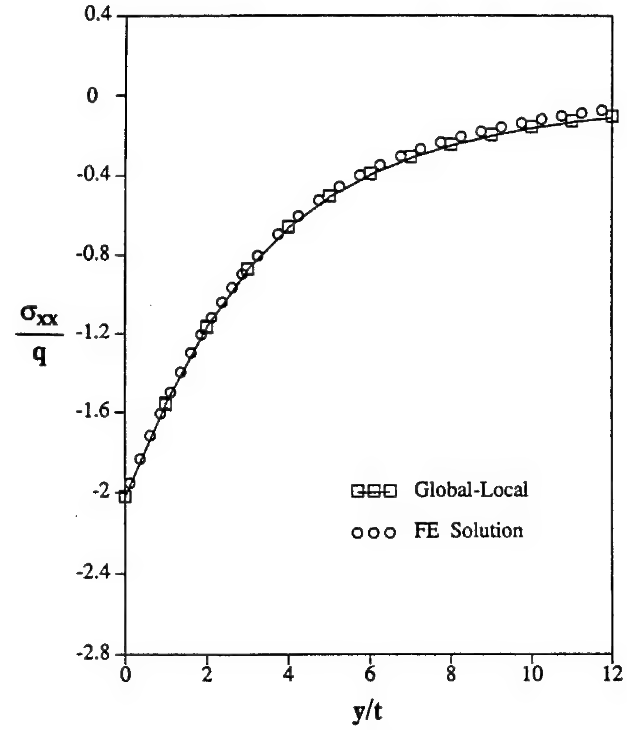
Distribution of σ_{xx}/q along $x/t = 0.05$ in the $[0/90]_{250}$ laminate for $a/t = 1$.



Distribution of σ_{xx}/q along $x/t = 0.05$ in the $[0/90]_{250}$ laminate for $a/t = 10$.

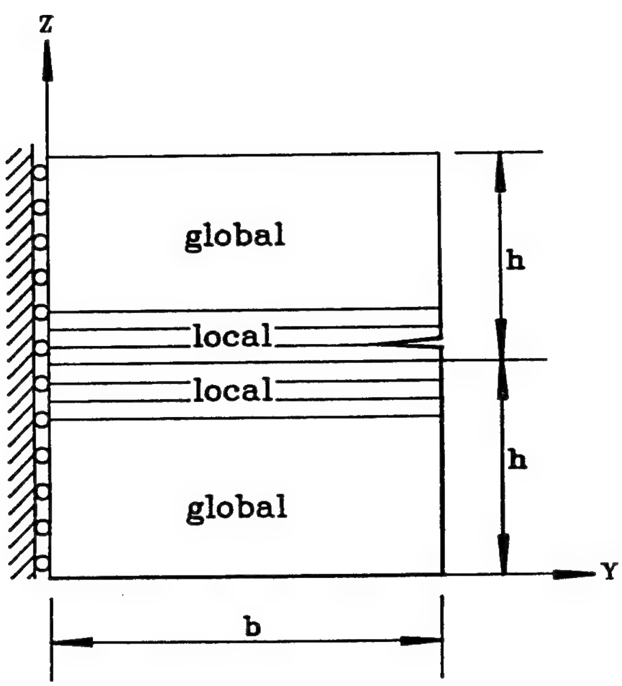


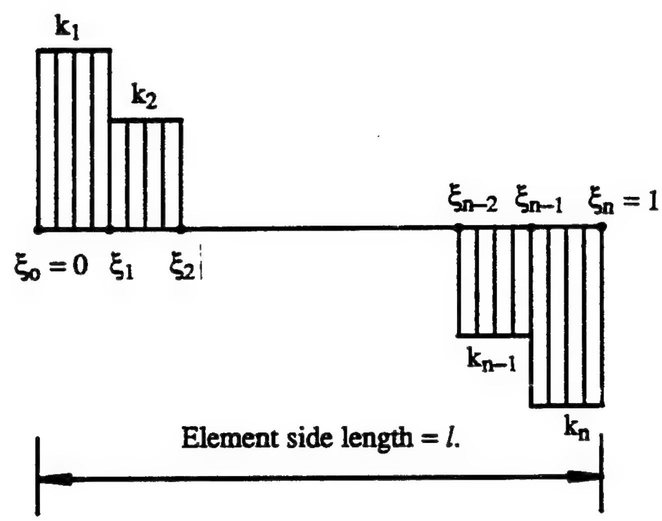
Distribution of σ_{xx}/q along $x/t = 0.05$ in the $[45/{-45}]_{250}$ laminate for $a/t = 1$.



Distribution of σ_{xx}/q along $x/t = 0.05$ in the $[45/{-45}]_{250}$ laminate for $a/t = 10$.

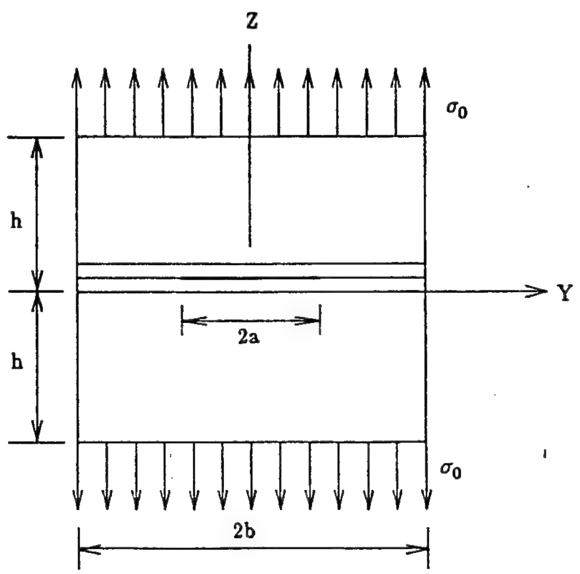
GLOBAL-LOCAL APPROACH

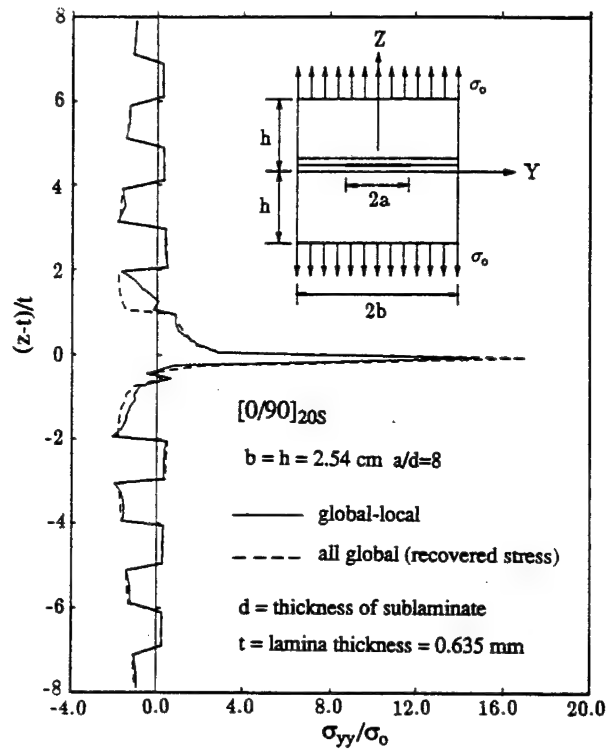




Added tractions on boundary.

INTERLAMINAR CRACK





Inplane stress σ_{yy} distribution along y/a = 1.0156.

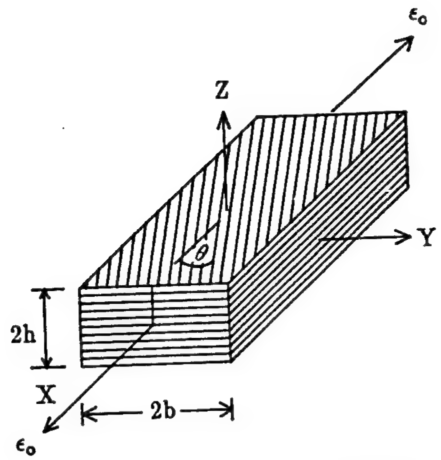
Interlaminar Crack Energy Release Rates $\bar{G} = GE_2/(\sigma_o^2 a)$ for $[0/90]_{20S}$ Laminate

a/d	0.1	0.5	2.0	8.0
$\bar{G}_I$ (all local)	2.352	2.247	2.257	2.824
$\bar{G}_I$ (local+global)	2.353	2.250	2.258	2.820
$\bar{G}_{II}$ (all local)	0.135	0.177	0.170	0.107
$\bar{G}_{II}$ (local+global)	0.136	0.177	0.169	0.107
$\bar{G}=\bar{G}_I+\bar{G}_{II}$ (all local)	2.487	2.424	2.427	2.931
$\bar{G}=\bar{G}_I+\bar{G}_{II}$ (local+global)	2.489	2.427	2.427	2.927
$\bar{G}$ (global)	2.373	2.387	2.395	2.925
$\bar{G}^*$ (global)	2.380	2.391	2.402	2.933

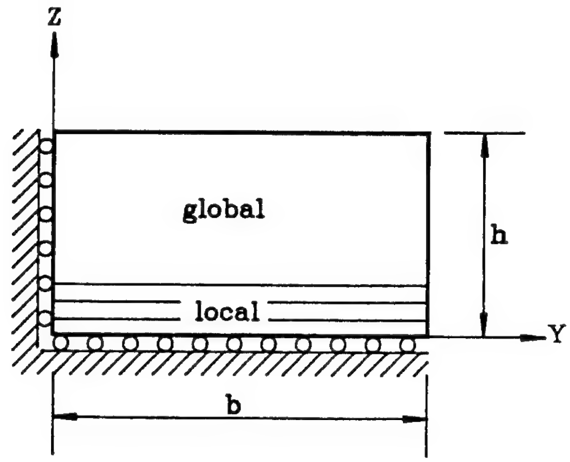
d = thickness of sublaminate

$\bar{G}^*$ (global) = solution without adding unbalanced nodal forces

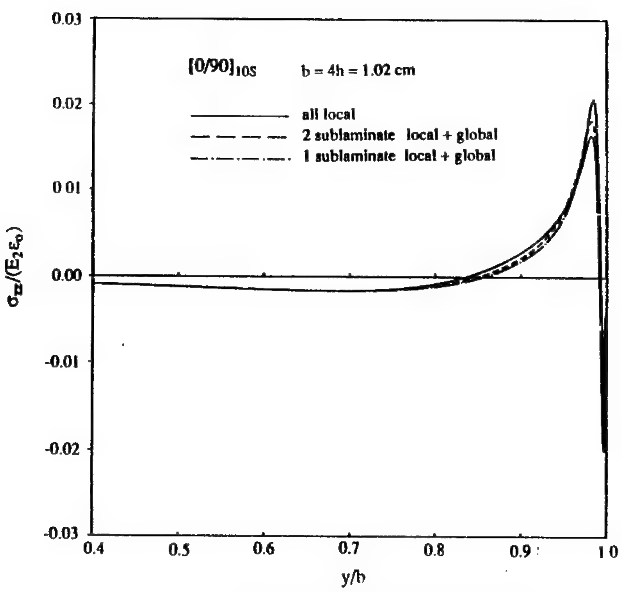
FREE EDGE STRESSES



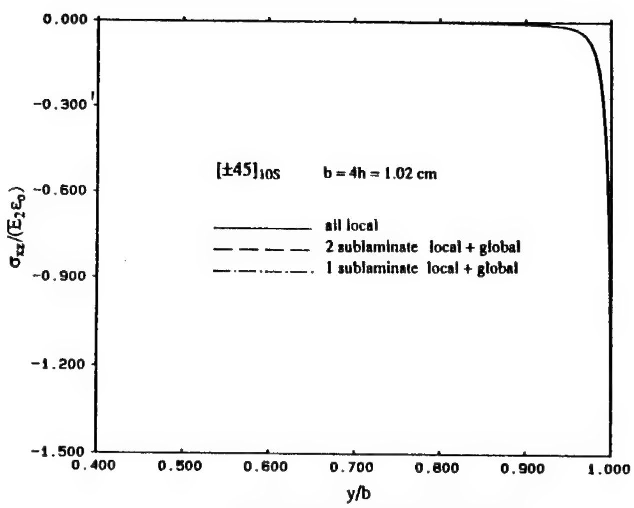
Uniform strain ϵ_o in x direction.



Finite element mesh for symmetric geometry.

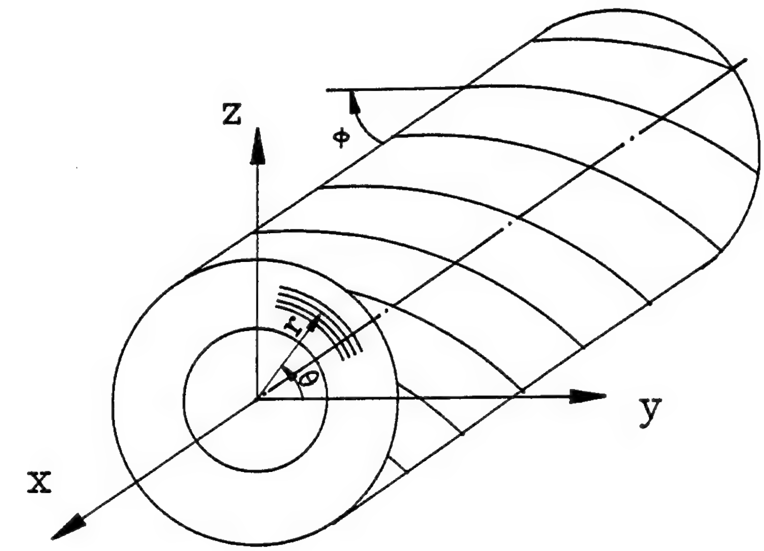


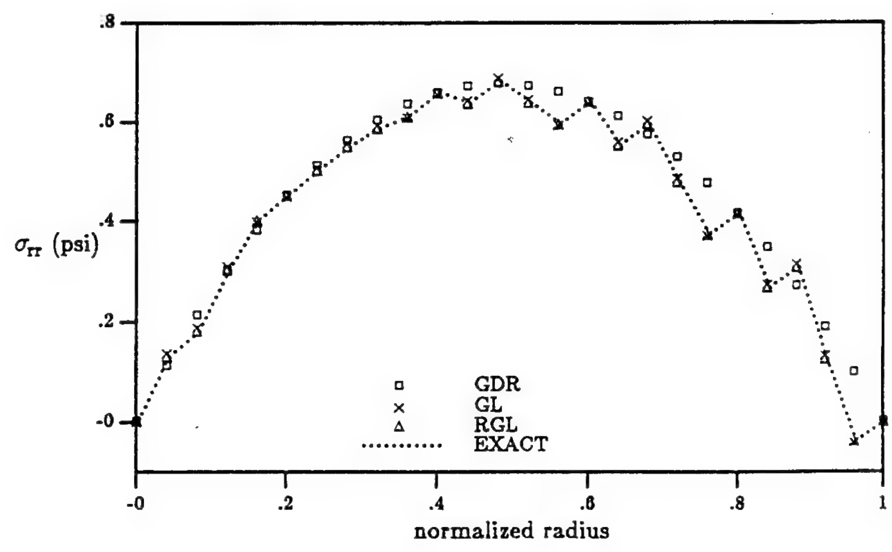
Interlaminar normal stress σ_{zz} at interface z=t.



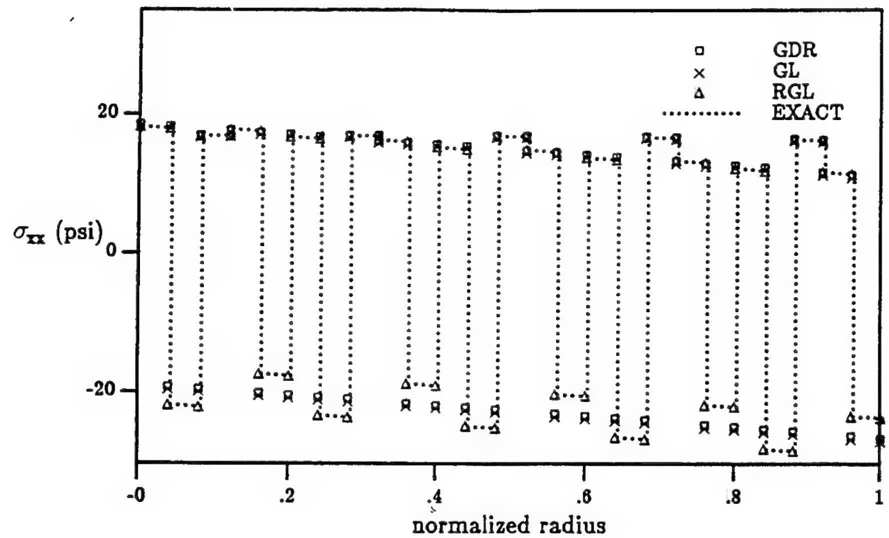
Interlaminar shear stress σ_{xz} at interface z=t.

THERMAL STRESSES IN THICK LAMINATED CYLINDER

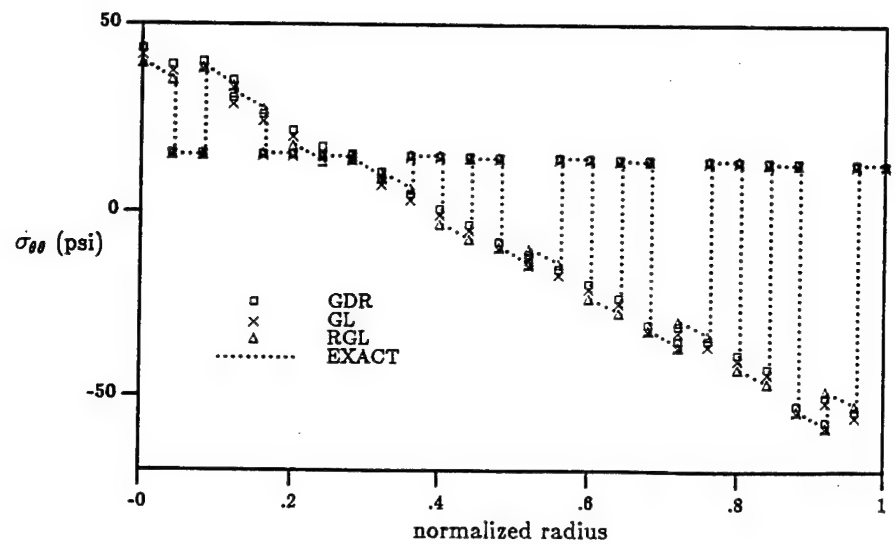




Radial stress σ_{rr} in $[75/15/90/-75/-15]_5$ for $\Delta T = -1°F$



Axial stress σ_{xx} in $[75/15/90/-75/-15]_5$ for $\Delta T = -1°F$



Hoop stress $\sigma_{\theta\theta}$ in $[75/15/90/-75/-15]_5$ for $\Delta T = -1°F$

QUANTITATIVE ULTRASONICS MEASUREMENTS IN COMPOSITE MATERIALS†

Wolfgang Sachse

Department of Theoretical and Applied Mechanics
Cornell University, Ithaca, New York - 14853

1 Introduction

This paper summarizes our recent work whose focus is to the *quantitative* ultrasonic measurements in composite materials. Our work has focused on the development of new analytical and measurement tools for characterizing these materials. In particular, we have developed the following: (1) New, absolute techniques for the measurement of frequency-dependent ultrasonic wavespeeds and attenuations; (2) Inversion techniques for determining all the elastic constants of these materials from measurements in non-prinicipal directions; (3) Development of *neural-like* processing algorithms for characterizing sources of emission; (4) Investigation of the interfacial properties between fiber and matrix in single-fiber composites; and (5) Extension of conventional acoustic emission source location techniques to be applicable to sources of emission in anisotropic materials. A number of papers describing this work have, or will shortly, appear in print and hence, here we merely summarize the most essential results and refer the interested reader to the more detailed articles.

By *quantitative ultrasonic measurements*, we mean those ultrasonic techniques which rely on a theoretical basis for understanding the propagation of transient elastic waves through a bounded structure, a broadband, small aperture ultrasonic source or excitation and a receiving transducer whose transduction characteristics are known *a priori* or which can be determined in a calibration experiment and signal processing algorithms for recovering the characteristics of either the source or the medium from the detected signals [1].

2 Ultrasonic Testing

When quantitative ultrasonic measurements are made with a known, small-aperture, broadband source, the recently-developed *point-source/point-receiver* (or *PS/PR*) technique shown in Fig. 1 is realized. The technique possesses several desirable characteristics which are particularly useful for making measurements on composite specimens. To implement the *PS/PR* testing method, a minimal amount of specimen surface preparation is needed and the surfaces of the composite specimen need not be planar nor parallel. Furthermore, information regarding the propagation characteristics of both longitudinal and shear waves is possible from a single waveform and the technique can be used with excitation sources whose time characteristics possess high energies at low frequencies, facilitating measurements in ultra-attenuative composite materials.

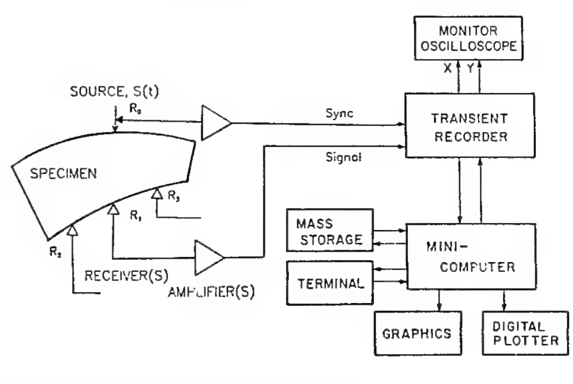


Figure 1: Schematic of the *PS/PR* composite materials testing system.

† Work supported by ONR (Solid Mechanics Program), Contract N00014-85-K-0595.

An overview of the *PS/PR* technique and its application to characterize composite materials have appeared in several papers [2,3,4,5]. Requirements pertaining to the characteristics of the sources (or actuators) as well as the receiving sensors which are required to successfully effect this technique are discussed in Ref. [6]. In some applications, conventional, piezoelectric transducers can be used, but the signals often require additional processing.

The importance of having a theoretical wave propagation algorithm available for computing the expected ultrasonic wave signals is that processing algorithms can be developed and tested with synthetic signals for extracting particular information from them. The focus of past work has been on the propagation of transient waves in bounded materials which are elastic and isotropic. We have recently developed algorithms for computing the transient response of an isotropic, *viscoelastic* plate to a force excitation applied normal to the surface of the plate [7,8,9]. A sample result for a Voigt-like material is shown in Fig. 2(a). The vertical displacement signals are the computed waveforms expected at *epicenter* (directly under the source point) and at one thickness removed from it. We have used these algorithms to develop and to verify new signal processing procedures by which one can extract from the magnitude and phase spectra of the signals detected at two receiver locations, the frequency-dependent attenuation and wavespeeds of the specimen material. An example is shown in Fig. 2(b). The curves correspond to the input and recovered frequency-dependent wavespeed and attenuation values used to compute the synthetic waveforms shown in Fig. 2(a).

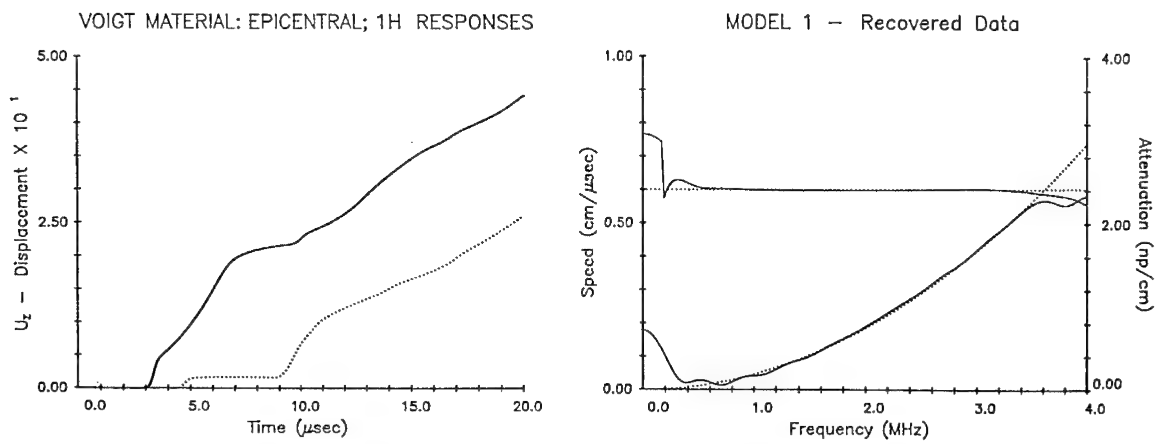


Figure 2: (a) Synthetic ultrasonic signals in a Voigt-like viscoelastic material. (b) Input and recovered wavespeed and attenuation values.

Another significant development has been the implementation of an inversion scheme by which the measured *PS/PR* longitudinal and shear wavespeed data is processed to recover both Lamé elastic constants of an elastically isotropic composite material, such as many metal-matrix or chopped fiber composites. Furthermore, by using an array of sensors to detect the signals at points equi-spaced about the source point, the orientation dependence of the wavespeeds in the material can be determined. As expected, this dependence is strongly dependent on the elastic anisotropy of the composite material [2,3].

An algorithm was recently developed by which wavespeed measurements made on arbitrary non-principal planes in a specimen can be used to recover the complete matrix of elastic constants of the material [10,11]. The determination relies on the measurements of the quasi-P- and quasi-S-wave arrival times for source-receiver configurations whose number significantly exceeds the number of elastic constants to be determined.

The elastic constants of the material are recovered using an optimization algorithm. Experimental results are presented in Fig. 3 for a transversely isotropic, uni-directional fiberglass/polyester. It was found that the non-linear fit between the measured and the recovered longitudinal slowness values is excellent. Some discrepancies are observed in the data for the two shear modes. These are shown to be related to the complexity of the detected signals.

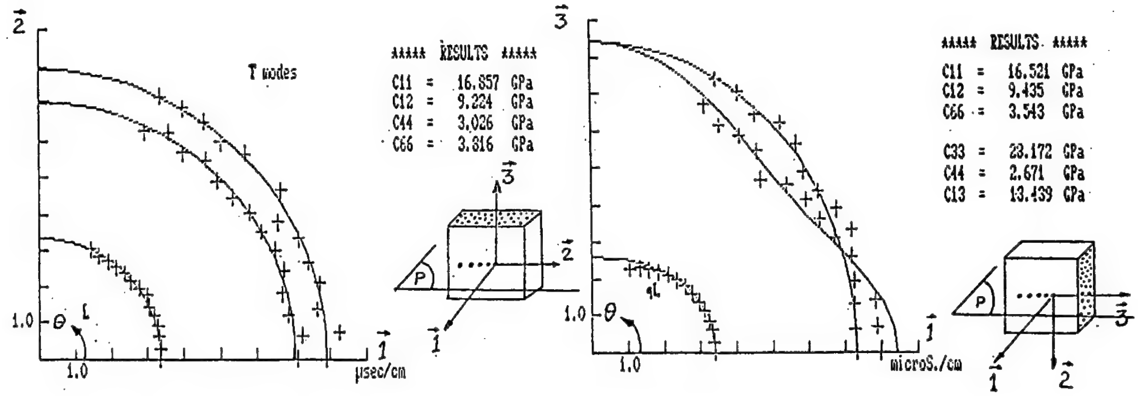


Figure 3: Elastic constants of uni-directional fiberglass/polyester. (a) Scan in isotropic plane (1,2); (b) Scan in anisotropic plane (1,3).

3 Intelligent, Neural-like Processing of Signals

An important, recent development has been the formulation of a *neural-like* processing procedure for analyzing ultrasonic signals to recover missing information in them. This missing information may be related to the source of the sound or to the waveform (which, in turn, is related to the material) [12]-[16].

Recognizing that most quantitative acoustic emission source characterization tasks are experimentally and computationally a prohibitive, we have therefore explored a neural-like processing scheme as an alternative. In this approach, a system is taught and a *memory* is developed corresponding to known sources and materials. Unknown signals are then processed to recover the missing information. It has been shown that such processing yields an optimal solution to an inverse problem from the given data [13].

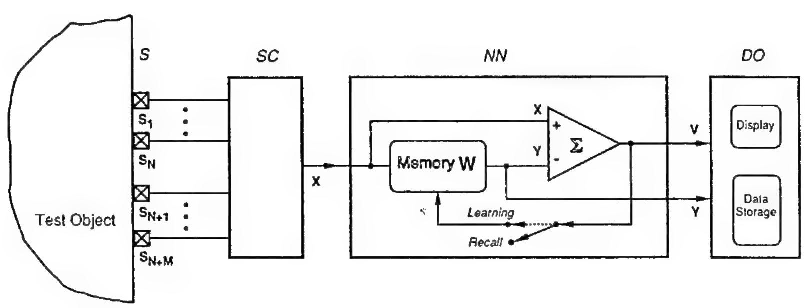


Figure 4: Neural-like ultrasonic signal processor.

' Our application of this approach is shown schematically in Fig. 4. Its features, which have been detailed in several publications [12,13,14], uses some of the fundamental principles of neural networks. We assume that the ultrasonic data can be characterized by a finite set of data supplied from an array of sensors together with selected features of the source or the medium. These data constitute a N-dimensional *pattern* vector given by $X = (X_1, X_2, \ldots, X_N)$ which is applied as input to the processor shown in the Fig. 4. For each input, the system responds with an output vector Y which is of the same dimension as X and which can be determined from the linear matrix equation

$$Y = \mathbf{W} \cdot X$$

where the matrix $\mathbf{W}$ represents the response function or *memory* of the system. In order to obtain an *associative* operation of the processing system, we assume that the system adapts to the input vectors such

that the *discrepancy* or *novelty* between the input and output vectors given by

$$V = X - Y = X - \mathbf{W}X \tag{1}$$

is reduced with a repetition of the inputs. This is possible with the feedback loop shown in Fig. 4. The adaptive law of the sytem which governs how the memory develops is similar to that used in other applications and is expressed by

$$\Delta\mathbf{W} = CV \otimes X^T \tag{2}$$

Here C is an *adaptation* constant and X^T denotes the transposed pattern vector. As input vectors are presented to the system, the result is the formation of the memory matrix $\mathbf{W}$ from an initially empty state, i. e. $\mathbf{W_0} = 0$. This resembles a *learning* process during which, the system adapts to the input so that the output vectors resemble the input vectors. If a new input vector is presented to the system, the generated output vector is a linear mixture of all the previously presented pattern vectors which most closely correlate to the new one. Solutions to both forward and inverse ultrasonic problems have been found with this processing system. In particular, the system has been demonstrated with several simple source location and source characterization problems [12,13]. They have included: Linear and two-dimensional source location problems; combined one-dimensional source location and scalar source characterization problems and the characterization of simple vector sources.

An example, shown in Fig. 5(a) depicts the measurements being made in a thick, anisotropic graphite-epoxy composite for which no Green's function is yet available. Two miniature, broadband piezoelectric transducers were mounted 6 in. apart on the surface of the slightly curved composite specimen which was 1.5 in. thick. The signals from the two sensors were amplified, recorded by a multi-channel waveform recording system. The processing system was trained with two source parameters: The location of the point of impact and the size of a steel ball causing the impact. The training signals are shown in Fig. 5(b). The memory was then developed as described above with the results shown in Fig. 5(c). Once the memory has been developed, missing information in signals presented to the system can be recovered. A tabulation of the results is listed in Fig. 5(d). It is seen that while in some cases, there are differences between the actual and recovered data, the results look promising.

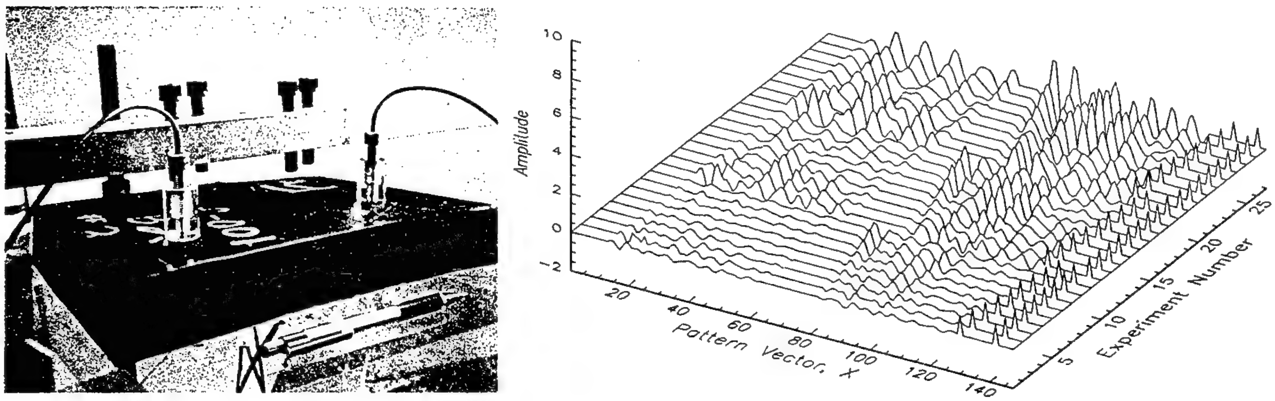
4 Acoustic Emission

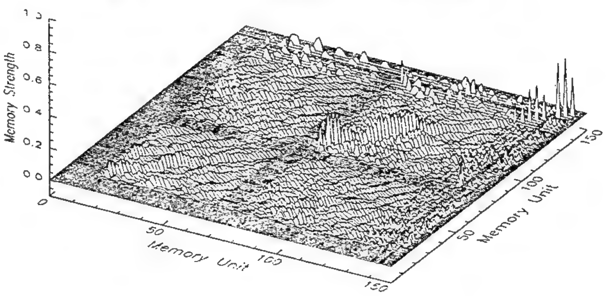
4.1 Single-fiber Composites

In the *quantitative acoustic emission* source characterization procedure, the detected signals are deconvolved with the known characteristics of the specimen and transducer to recover the characteristics of the source [1]. The characterization of various fiber and matrix failure modes using such techniques has to date not yet been possible. Instead, we have utilized conventional acoustic emission techniques to detect and to monitor the progression of failure in ideal, *single fiber composite* (or *SFC*) specimens [17,18]. Such measurements have as their aim an investigation of the progression of failure along a fiber. We have used this testing procedure to investigate how the transfer of shear forces from the matrix through the fiber/matrix interfaces is affected as the fiber fractures along its length during a uniaxial loading test and have developed a procedure for recovering the interfacial shear strength of the fiber/matrix interface. Also, the fiber fragmentation data which is determined in such a test has been important to several recent developments of the statistical theories of failure of composites.

4.2 Source Location in Composite Materials

The location of source of emission in an anisotropic material can be characterized, it must be located in a structure. Recently, source location algorithms by which the source location can be determined in anisotropic, composite specimens have been demonstrated [19,20]. The method is applicable for a source in an anisotropic solid of arbitrary symmetry as long as the principal acoustic axes of the material are known *a priori*. It was





Results for the data file: MURR01.DAT Generated: 16-Jul-88

			Locations		Impactor Size	
			Actual	Recovered	Recovered	Actual
Test:	1	Descriptor values:	3.0	2.9	5.4	5
Test:	2	Descriptor values:	4.0	3.2	7.9	7
Test:	3	Descriptor values:	4.0	3.4	8.1	7
Test:	4	Descriptor values:	3.0	4.0	3.9	3
Test:	5	Descriptor values:	5.0	4.6	7.3	7
Test:	6	Descriptor values:	1.0	1.7	5.6	5
Test:	7	Descriptor values:	5.0	4.3	5.6	5
Test:	8	Descriptor values:	2.0	2.0	8.4	7
Test:	9	Descriptor values:	2.25	2.8	4.1	3
Test:	10	Descriptor values:	2.25	2.0	6.7	5

Figure 5: Characterization of impact sources on a 1.5,in. thick graphite/epoxy using ***neural-like*** signal processing. (a) Experimental setup; (b) Pattern vectors; (c) Developed memory; (d) Sample results of the processing.

shown that from the time-of-flight differences of particular features in the waveforms detected by any pair of sensors a set of non-linear transcendental equations can be formed in which the coefficient of each term in the equations is related to the time-of-flight differences, the geometrical parameters of the array and to the wave speeds of quasi-waves propagating along each source/receiver path. For waves propagating in principal planes, the analytical expressions for the wave speed values are used. Extension to non-principal planes is obtained by computing the eigenvalues of the *Green-Christoffel* tensor. Determination of the optimum location of the source is found by minimizing the Euclidean functional associated with the set of transcendental non-linear equations. The results obtained with numerical simulations of two- and three-dimensional source location problems are presented to illustrate several characteristic features of the solution. Also shown are the results of two-dimensional source location measurements made on specimens of a uni-directional fiber glass reinforced composite material. The results demonstrate the efficiency of the algorithm in locating a source of emission.

References

[1] W. Sachse, "Applications of Quantitative AE Methods: Dynamic Fracture, Materials and Transducer Characteristics", in *Solid Mechanics Research for Quantitative Nondestructive Evaluation*, J. D. Achenbach and Y. Rajapakse, Eds., Martinus Nijhoff Publ., Dordrecht (1987), pp. 41-64.

[2] W. Sachse and K. Y. Kim, "Point-Source/Point-Receiver Materials Testing", in *Review of Quantitative Nondestructive Evaluation*, **6A**, D. O. Thompson and D. E. Chimenti, Eds., Plenum Press, New York (1986), pp. 311-320. Also, in *Ultrasonic Materials Characterization II*, J. Boussière, J. P. Monchalin, C. O. Ruud and R. E. Green, Jr., Eds., Plenum Press, New York (1987), pp. 707-715.

[3] W. Sachse and K. Y. Kim, "Quantitative AE and Failure Mechanics of Composite Materials", in *Proceedings of the Conference on NDE of Advanced Materials and Composites*, Colorado Springs, Colorado (1986); also, *Ultrasonics*, **25**, 195-203 (1987).

[4] W. Sachse and K. Y. Kim, "Novel Approaches for the Ultrasonic NDE of Thick and Other Composites", in *Review of Progress in Quantitative Nondestructive Evaluation*, **8B**, D. O. Thompson and D. E. Chi-

menti, Eds., Plenum Press, New York (1988), pp. 1473-1480.

[5] W. Sachse, B. Castagnede, I. Grabec, K. Y. Kim and R. L. Weaver, "Recent Developments for the Quantitative Ultrasonic NDE of Thick and Other Composites", Materials Science Center Report #6575 (November 1988). In Press: *Ultrasonics.*

[6] W. Sachse, "Transducer Considerations for Point-Source/Point-Receiver Materials Measurements", in *Ultrasonics International '87: Conference Proceedings*, Butterworth Scientific, Ltd., Guildford, Surrey, UK (1987), pp. 419-425.

[7] R. L. Weaver and W. Sachse, "Asymptotic Viscoelastic Rays in a Thick Plate", T & AM Preprint (June 1988). In Press: *Journal of Applied Mechanics.*

[8] R. L. Weaver, W. Sachse and L. Niu, "Transient Ultrasonic Waves in a Viscoelastic Plate: Theory", *Journal of the Acoustical Society of America*, **85**(6), 2255-2261 (1989).

[9] R. L. Weaver, W. Sachse and L. Niu, "Transient Ultrasonic Waves in a Viscoelastic Plate: Applications to Materials Characterization", *Journal of the Acoustical Society of America*, **85**(6), 2262-2267 (1989).

[10] B. Castagnede and W. Sachse, "Optimized Determination of Elastic Constants of Anisotropic Solids from Wavespeed Measurements", in *Review of Progress in Quantitative Nondestructive Evaluation*, **8B**, D. O. Thompson and D. E. Chimenti, Eds., Plenum Press, New York (1988), pp. 1855-1862.

[11] B. Castagnede, J. T. Jenkins, W. Sachse and J.-S. Baste, "Optimal Determination of the elastic constants of composite materials from ultrasonic wavespeed measurements", Materials Science Center Report #6688, (May 1989). In Press: *Journal of Applied Physics.*

[12] I. Grabec and W. Sachse, "Application of an Intelligent Signal Processing System to Acoustic Emission Analysis", *Journal of the Acoustical Society of America*, **85**(3), 1226-1235 (1989).

[13] I. Grabec and W. Sachse, "Experimental Characterization of Ultrasonic Phenomena by a Learning System", Materials Science Center Report #6447 (May 1988). In Press: *Journal of Applied Physics.*

[14] W. Sachse and I. Grabec, "Experimental Characterization of Ultrasonic Phenomena by a Neural-like Learning System", in *Review of Progress in Quantitative Nondestructive Evaluation*, **8A**, D. O. Thompson and D. E. Chimenti, Eds., Plenum Press, New York (1988), pp. 649-656.

[15] I. Grabec and W. Sachse, "Application of an Intelligent Signal Processing System to Acoustic Emission Analysis", in: *Progress in Acoustic Emission IV*, I. Kimpara, Ed., Japanese Society of NDI, Tokyo (1988), pp. 75-80.

[16] W. Sachse, "The Processing of AE Signals", in: *Progress in Acoustic Emission IV*, I. Kimpara, Ed., Japanese Society of NDI, Tokyo (1988), pp. 26-38. (Submitted to: *Journal of Acoustic Emission*).

[17] A. N. Netravali, D. Stone, S. Ruoff and L. T. T. Topoleski, "Continuous Micro-indenter Push-through Technique for Measuring Interfacial Shear Strength of Fiber Composites", *Composites Science and Technology*, **34**, 289-303 (1989).

[18] A. N. Netravali, L. T. T. Topoleski, W. Sachse and S. L. Phoenix, "An Acoustic Emission Technique for Measuring Fiber Fragment Length Distributions in the Single-fiber Composite Test", *Composites Science and Technology*, **35**, 13-29 (1989).

[19] B. Castagnede, K. Y. Kim and W. Sachse, "Localisation de sources d'émission acoustique dans un matériau composite" ("Acoustic Emission Source Location in a Composite Material"), *C. R. Acad. Sci. Paris*, **t. 307, Série II**, 1595-1600 (1988).

[20] B. Castagnede, K. Y. Kim and W. Sachse, "Location of Point-like Acoustic Emission Sources in Anisotropi Plates", *Journal of the Acoustical Society of America*, **86**(3), 1161-1171 (1989).

DELAMINATION TOUGHNESS TESTING WITH THE MIXED MODE BENDING APPARATUS

James R. Reeder and J. H. Crews, Jr.

NASA Langley Research Center
Hampton, VA 23665

ABSTRACT

Because composite structures can delaminate under complex loadings, the delamination fracture toughness of composite materials should be measured with mixed-mode loading. The new mixed-mode delamination test described in this talk can apply different amounts of mode I (opening) and mode II (sliding shear) loadings. This new test, called a mixed-mode bending (MMB) test [1], combines the mode I double cantilever beam (DCB) test and the mode II end notch flexure (ENF) test. This combination uses a lever to simultaneously apply DCB and ENF type loadings. By varying the loading position on the lever, the mixture of mode I and mode II loading can be changed. The effects of this mixed-mode loading on delamination were analyzed in terms of the mode I and mode II components of strain-energy-release rate (G_I and G_{II}, respectively).

The MMB test solves many of the problems that exist with other mixed-mode delamination tests. The edge delamination tension (EDT) test, the cracked lap shear (CLS) test, and the mixed-mode flexure test all require different types of specimens to test at different G_I/G_{II} ratios. The Arcan test and the EDT involve unstable delamination growth which can be difficult to analyze. Also, the EDT, CLS, and ARCAN tests all require a numerical analysis since closed-form stress analyses are not available. The variable-ratio mixed-mode test cannot test with a constant G_I/G_{II} ratio, and the asymmetric bend test requires a complex loading system.

The MMB test uses a single test specimen configuration to test over a wide range of mixed-mode ratios. This is the same specimen configuration that is widely used in DCB and ENF testing. As a result, mixed-mode and pure mode tests can all be conducted with the same specimen configuration. Furthermore, all tests can be performed in a standard displacement-control test machine.

The specimen was first analyzed using finite elements to calculate strain-energy-release rates. The finite element analysis showed that the G_I/G_{II} ratio stays nearly constant with delamination length for the test range (delamination lengths from 25 mm to 45 mm). Within this test range, the stability of the delamination growth was also considered. Under displacement control, most of the G_I/G_{II} cases were found to be stable for much of the delamination growth range.

A major advantage of the MMB test configuration is that it can also be modeled with a closed-form beam-theory stress analysis. Superposition principles were used to combine closed-form analyses of the DCB and ENF tests into a closed-form model for the MMB test. The resulting closed-form equations for G_I and G_{II} were then modified to improve their accuracy. The first modification accounted for shear deformation [2] of the beam and the second accounted for rotations at the delamination tip (beam on elastic foundation correction) [3]. The modified equations were then compared to the finite element results; strain-energy- release rates agreed within 6 percent.

The MMB test was used to measure the mixed-mode delamination toughness of AS4/PEEK (APC2), a very tough composite. For this study, three G_I/G_{II} ratios of 1/4, 1/1, and 4/1 were tested along with the two pure mode cases. The test specimens were made using a 24-ply unidirectional laminate and measured 25 mm by 153 mm. Each specimen contained a 13 μm thick Kapton insert at one end of the specimen to give an initial delamination length of 25 mm. All samples where precracked with a G_I/G_{II} ratio of 4/1 to a delamination length of about 30 mm. Each specimen was then loaded until the delamination grew. The delamination length and the load require for delamination growth were used in the closed-form equations to determine the mode I and mode II components of fracture toughness. The test results were presented as the mode I component of fracture toughness plotted against the mode II component.

The MMB delamination test described in this paper is rather simple and is believed to offer several advantages over most current mixed-mode test procedures.

REFERENCES

1. Reeder, J. R.; Crews, J. H., Jr.: "The Mixed-Mode Bending Method for Delamination Testing," 30th AIAA SDM conference proceedings, April 3-5,1989, Mobile, Alabama, pp. 1640-1647. (also NASA TM 100662)

2. Carlsson, L. A.; Gillespie, J. W.; and Pipes, R. B.: "On the Analysis and Design of the End Notched Flexure (ENF) Specimen for Mode II Testing," Journal of Composite Materials, Vol. 20, November 1986, pp. 594-604.

3. Kanninen, M. F.: "An Augmented Double Cantilever Beam Model for Studying Crack Propagation and Arrest," International Journal of Fracture, Vol. 9, No. 1, March 1973, pp. 83-92.

DELAMINATION TOUGHNESS TESTING WITH THE MIXED MODE BENDING APPARATUS

JAMES R. REEDER and JOHN H. CREWS, JR.

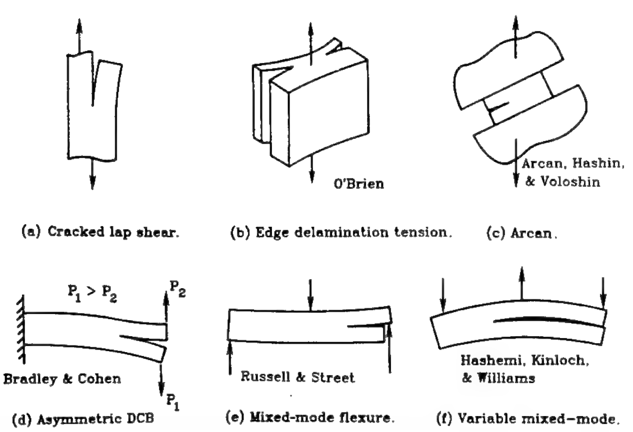
NASA Langley Research Center

Fourteenth Mechanics of Composites Review
Dayton, Ohio
October 31 - November 1, 1989

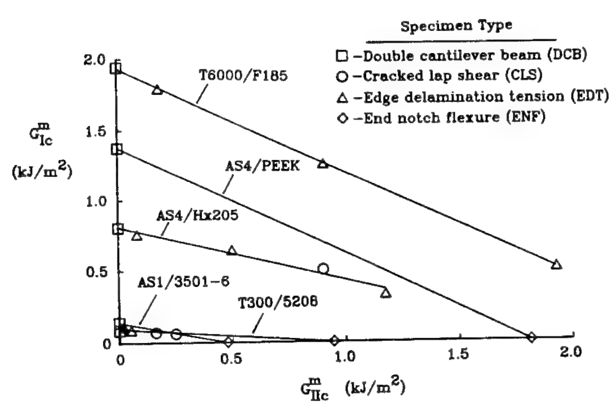
Objective: To develop a test to measure delamination fracture toughness with varying amounts of mode I and mode II loading

Outline:
- o Review of current mixed-mode delamination tests
- o Presentation of the mixed-mode bending test
- o Finite element analysis
- o Closed form analysis
- o Experimental results

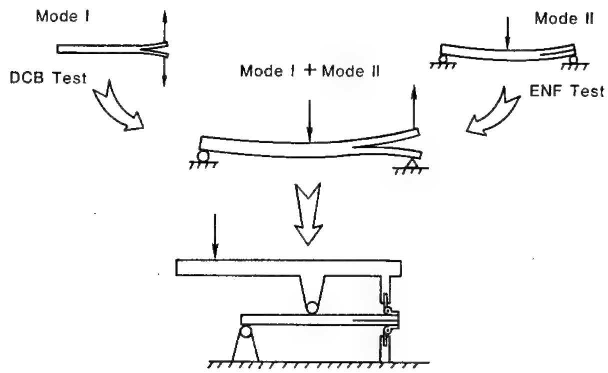
MIXED-MODE TEST SPECIMENS



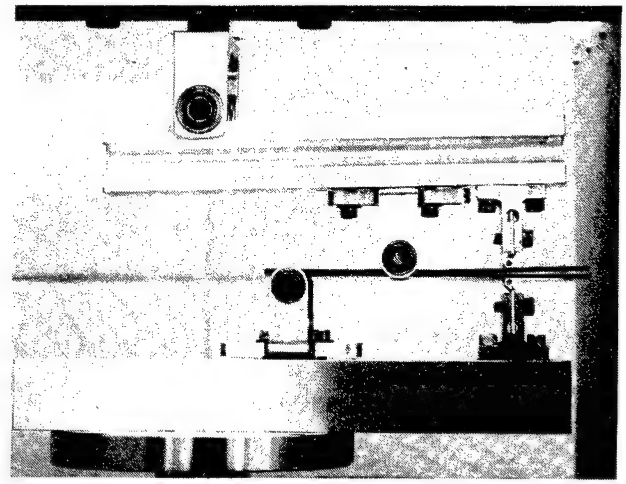
MIXED-MODE DELAMINATION TOUGHNESS



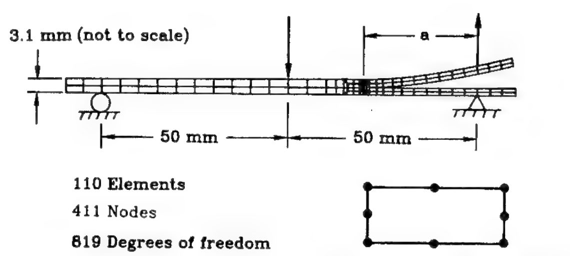
THE MIXED-MODE BENDING TEST



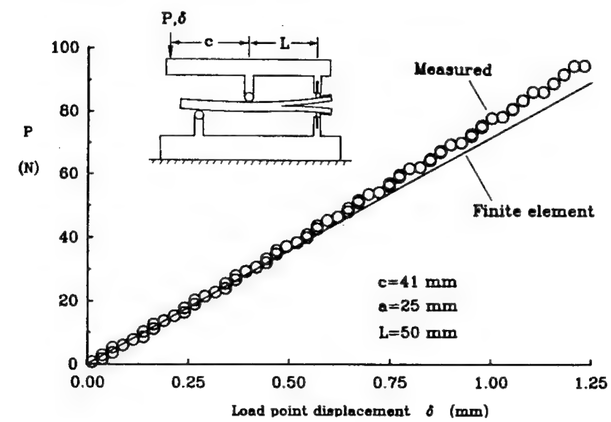
PHOTOGRAPH OF THE MIXED MODE BENDING APPARATUS



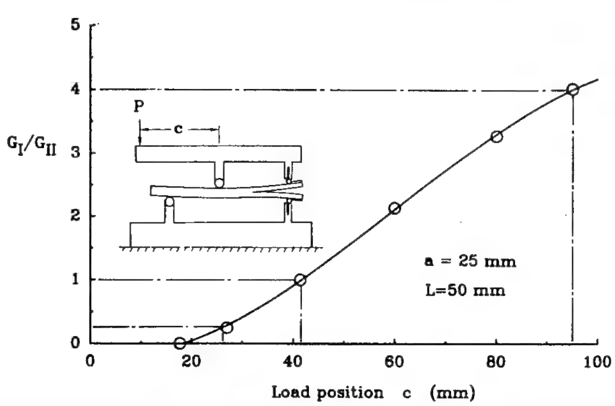
FINITE ELEMENT MODEL FOR THE MMB TEST



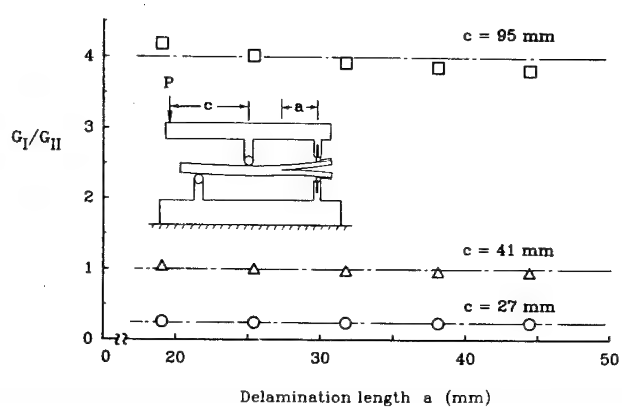
FINITE ELEMENT ANALYSIS VERIFICATION



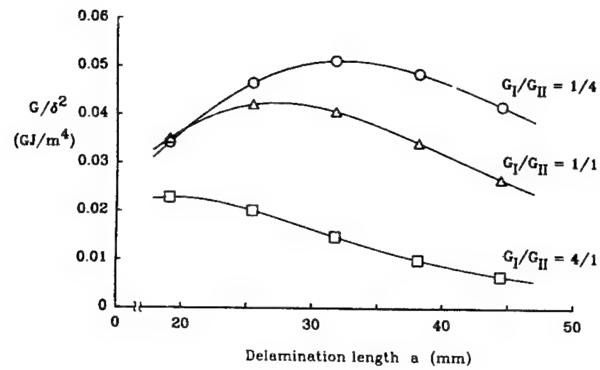
LOAD POSITION DETERMINATION



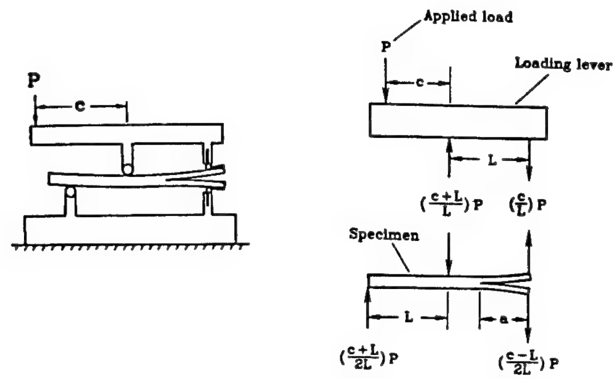
MIXED-MODE RATIO VARIATION



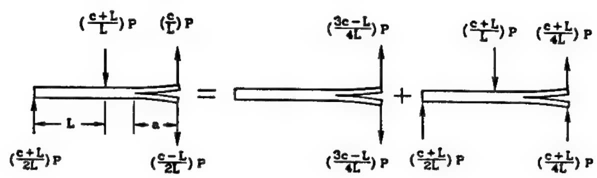
G VARIATION OF MIXED MODE TESTS



CLOSED FORM SOLUTION



SUPERPOSITION ANALYSIS



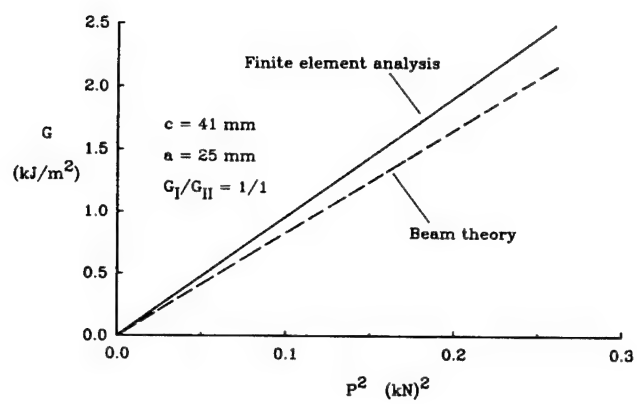
$$G_{II} = \frac{9a^2P^2}{16b^2h^3L^2E_{11}}(c+L)^2$$

$$G_I = \frac{3a^2P^2}{4b^2h^3L^2E_{11}}(3c-L)^2$$

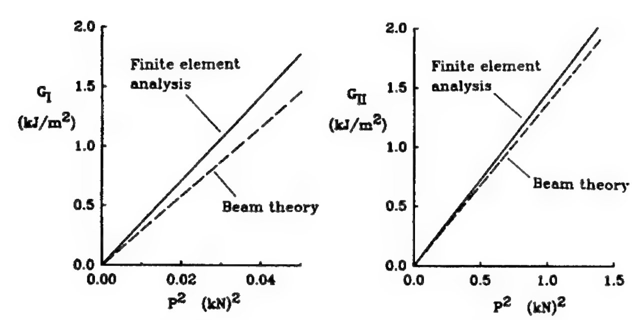
$$G = \frac{3a^2P^2}{16b^2h^3L^2E_{11}}\left[4(3c-L)^2+3(c+L)^2\right]$$

$$G_I/G_{II} = \frac{4}{3}\left[\frac{(3c-L)}{(c+L)}\right]^2$$

COMPARISON OF MODELS



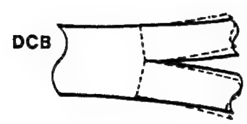
PURE MODE COMPARISON



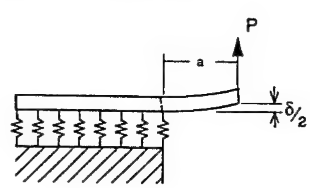
(a) Mode I

(b) Mode II

END ROTATION CORRECTION



BEAM ON AN ELASTIC FOUNDATION



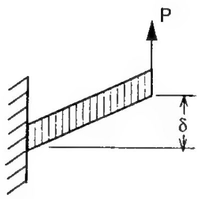
$$\delta = \frac{8P_I}{bh^3E_{11}}\left[a^3 + \frac{3a^2}{\lambda} + \frac{3a}{\lambda^2}\right]$$

$$\lambda = (3k/bh^3E_{11})^{1/4}$$

$$k = 2bE_{22}/h$$

$$G_I = \frac{12P_I^2}{b^2h^3E_{11}}\left[a^2 + \frac{2a}{\lambda} + \frac{1}{\lambda^2}\right]$$

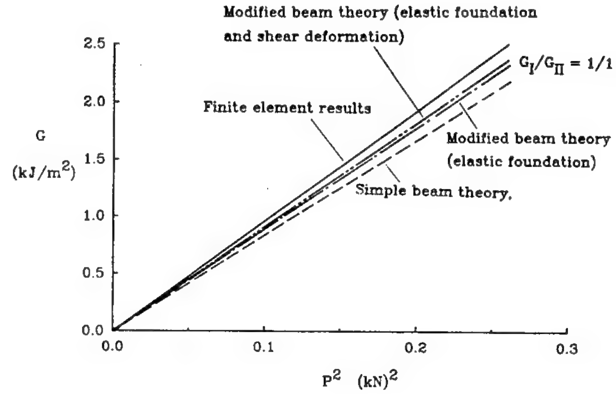
SHEAR TERM CORRECTION



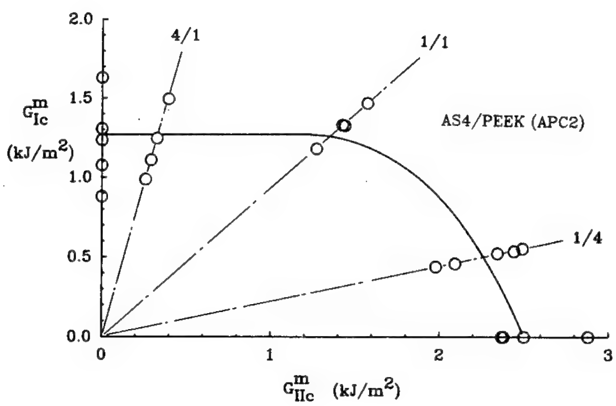
$$G_I = \frac{3P^2(3c-L)^2}{4b^2h^3L^2E_{11}}\left[a^2 + \frac{2a}{\lambda} + \frac{1}{\lambda^2} + \frac{h^2E_{11}}{10G_{13}}\right]$$

$$G_{II} = \frac{9P^2(c+L)^2}{16b^2h^3L^2E_{11}}\left[a^2 + \frac{0.2h^2E_{11}}{G_{13}}\right]$$

COMPARISON OF MODIFIED MODELS



MIXED-MODE DELAMINATION TOUGHNESS



SUMMARY

- o A new method for measuring mixed-mode delamination toughness was developed.
- o The MMB test can be modeled with a closed-form equations.
- o The G_I/G_{II} ratios varied by less than 6% during tests.
- o The MMB test was demonstrated with a tough thermoplastic composite over a wide range of G_I/G_{II} ratios.

TIME DEPENDENT BEHAVIOR OF HIGH TEMPERATURE METAL MATRIX COMPOSITES

BY

P. L. N. Murthy and C. C. Chamis

NASA Lewis Research Center
Cleveland, Ohio

ABSTRACT

The effects of time on the properties of metal matrix composites (MMC) are evaluated using a multi factor interaction (MFI) relationship. The MFI relationship is expressed in terms of products where each product term includes primitive material variables raised to an exponent. The primitive variables and exponent in each term can be suitably selected to represent the whole creep process (primary, secondary, e time tertiary). For example, the initial creep, constant creep rate, and the aging part are continuously represented by the same equation without breaking the time up into three traditional intervals. Since the MFI equation includes terms to account for temperature, stress rates, and cycles, it can be used to investigate respective coupling effects on the time dependent properties. The MFI relationship is coupled with nonlinear high temperature composite mechanics and integrated into a computer code METCAN (Metal Matrix Composites Analyzer). Application of METCAN to monotonic and cyclic loads is described in references 1 and 2.

The objective of the presentation is to describe the approach in some detail and present results to illustrate the relative influences of various couplings on time dependent properties. Thermal ratcheting is a specific case which is represented by rapid aging as the final time to fracture is approached.

Specific results are for: (1) unidirectional composites subjected to uniaxial loads and uniaxial loads with three different temperatures, and (2) angleplied laminate subjected to uniaxial load, bending load and temperature gradient through the thickness. The results for all are presented in terms of time dependent ply and matrix strains.

The results of the strains show also that the restraining effects (in situ behavior) causes the matrix to exhibit different time dependent behavior than would be expected from bulk observed behavior. This type of time dependent behavior cannot be identified or even inferred from conventional unidirectional composite creep tests. Although ply and constituent stress results are not included, they show stresses shifting, progressively from the softer matrix to the stiffer fibers.

The authors consider that this new capability in METCAN has the potential to predict the time dependent high temperature behavior of composite structures. Strategic experiments for its verification are still needed.

REFERENCES

1. C. C. Chamis, P. L. N. Murthy, and D. A. Hopkins: Computational Simulation of High Temperature Metal Matrix Composites Cyclic Behavior, NASA TM 102115, 1988.
2. P. L. N. Murthy, D. A. Hopkins, and C. C. Chamis: Metal Matrix Composite Micromechanics: In-Situ Behavior Influence on Composite Properties. NASA TM 102302, 1989.

TIME DEPENDENT BEHAVIOR OF HIGH TEMPERATURE METAL MATRIX COMPOSITES

BY

P. L. N. MURTHY AND C. C. CHAMIS

NASA Lewis Research Center

Cleveland, OH 44135

PRESENTATION FOR

DOD/NASA REVIEW OF THE MECHANICS OF COMPOSITES

OCTOBER 31 - NOVEMBER 1, 1989

DAYTON, OHIO

BACKGROUND

- High temperature composites are simultaneously subjected to loads and temperatures over a time period which cause coupled nonlinear behavior in the composite
- Quantification of time effect on this coupled nonlinear behavior is necessary in order to assess the durability/longevity of the composite in its intended hostile environment
- Recent research at Lewis focuses on the computational simulation of this coupled nonlinear behavior using a multi-factor interaction (MFI) relationship at the constituent material level in conjunction with nonlinear high temperature composite mechanics
- Application to static and cyclic mechanical and thermal loads showed promise of the effectiveness of the computational simulation approach
- Present efforts are to include the time dependence

PRESENTATION OUTLINE;

- o Background
- o Objective
- o Approach
  - Multi-factor interaction (MFI) relationship
  - High temperature nonlinear composite mechanics (METCAN)
- o Results
  - Unidirectional composite: Under uniaxial loads
  - Angle plied laminate:

    Axial

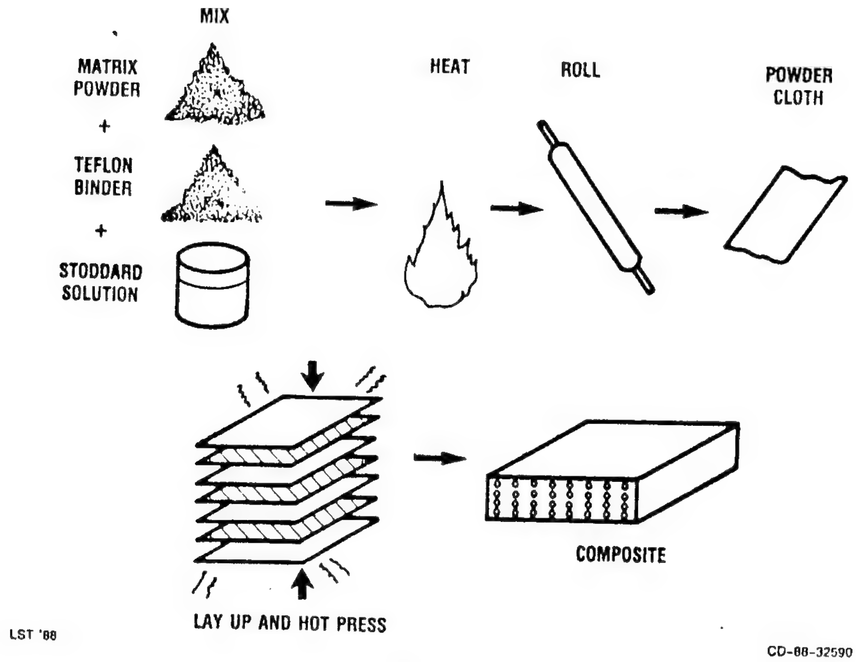
    Bending

    Thermal gradient
- o Conclusions

OBJECTIVE:

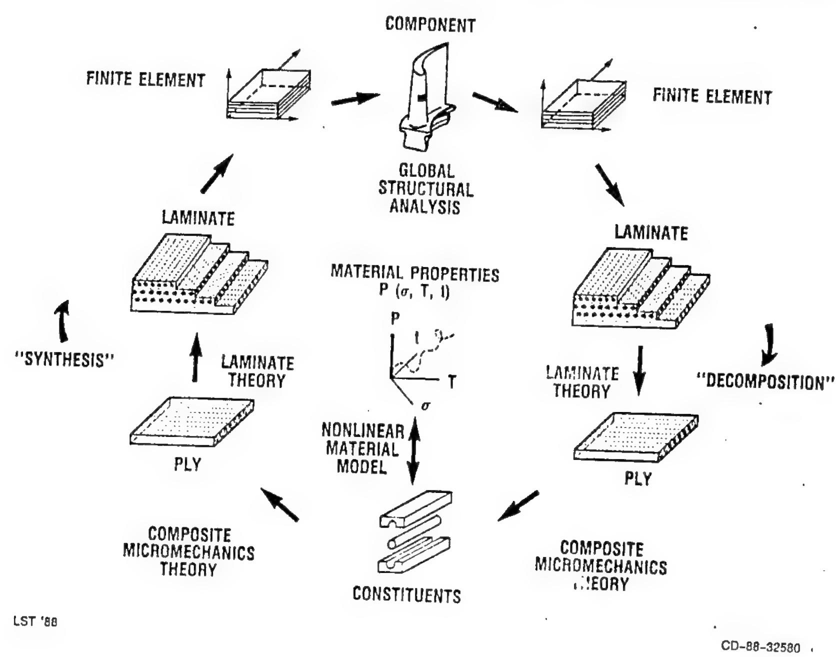
- o The objective of the presentation is to briefly describe the computational approach and present typical results to illustrate its potential

METAL-MATRIX COMPOSITE FABRICATION PROCESS



METCAN

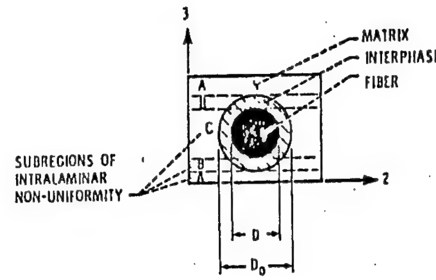
INTEGRATED APPROACH TO METAL-MATRIX COMPOSITE ANALYSIS



MULTIFACTOR INTERACTION RELATIONSHIP FOR IN SITU CONSTITUENT MATERIAL BEHAVIOR

$$\frac{P}{P_0} = \left[\frac{T_F - T}{T_F - T_0}\right]^n \left[\frac{S_F - \sigma}{S_F - \sigma_0}\right]^m \left[\frac{\dot{S}_F - \dot{\sigma}_0}{\dot{S}_F - \dot{\sigma}}\right]^\ell \left[\frac{\dot{T}_F - \dot{T}}{\dot{T}_F - \dot{T}_0}\right]^k \left[\frac{R_F - R}{R_F - R_0}\right]^p \cdots$$

$$\cdots \left[\frac{N_{MF} - N_M}{N_{MF} - N_{MO}}\right]^q \left[\frac{N_{TF} - N_T}{N_{TF} - N_{TO}}\right]^r \left[\frac{t_F - t}{t_F - t_0}\right]^s \cdots$$

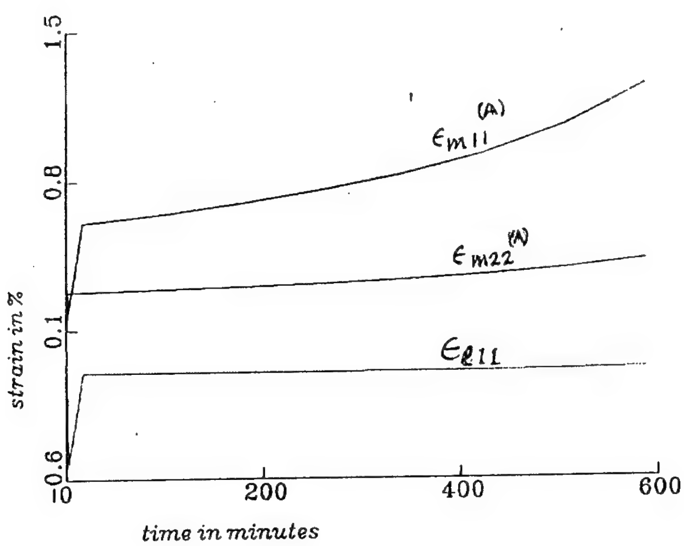


MOTIVATION:

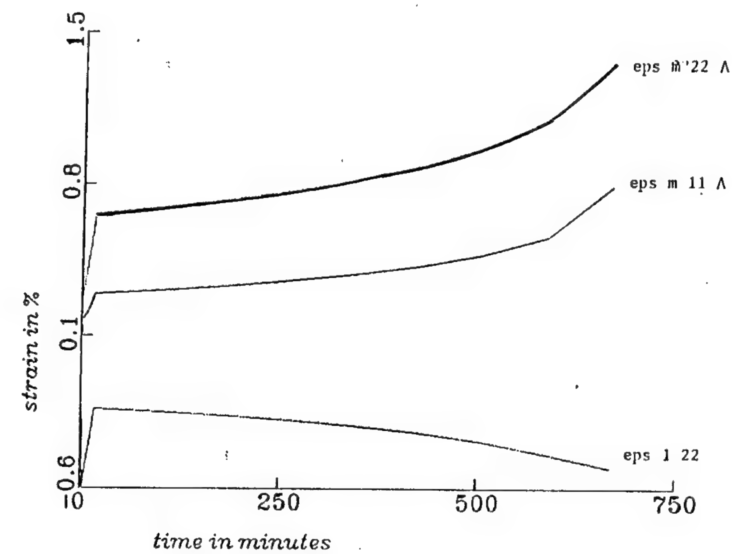
- o GRADUAL EFFECTS DURING MOST RANGE, RAPIDLY DEGRADING NEAR FINAL STAGES
- o REPRESENTATIVE OF THE IN SITU BEHAVIOR FOR FIBER, MATRIX, INTERPHASE, COATING
- o INTRODUCTION OF PRIMITIVE VARIABLES (PV)
- o CONSISTENT IN SITU REPRESENTATION OF ALL CONSTITUENT PROPERTIES IN TERMS OF PV
- o ROOM TEMPERATURE VALUES FOR REFERENCE PROPERTIES
- o CONTINUOUS INTERPHASE GROWTH
- o SIMULTANEOUS INTERACTION OF ALL PRIMITIVE VARIABLES
- o ADAPTABILITY TO NEW MATERIALS
- o AMENABLE TO VERIFICATION INCLUSIVE OF ALL PROPERTIES
- o READILY ADAPTABLE TO INCREMENTAL COMPUTATIONAL SIMULATION

TIME-DEPENDENT PLY AND MATRIX STRAINS IN A UNIDIRECTIONAL COMPOSITE UNDER LONGITUDINAL STRESS

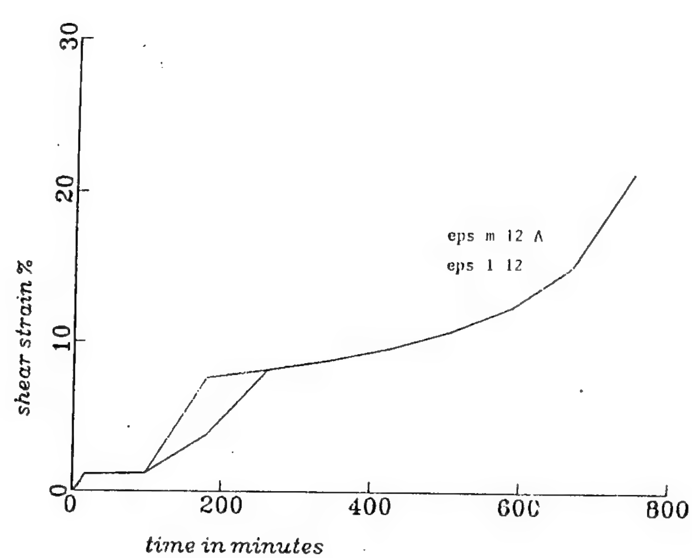
(SiC/Ti-15.3.3.3; 0.3 FVR; 100 ksi)



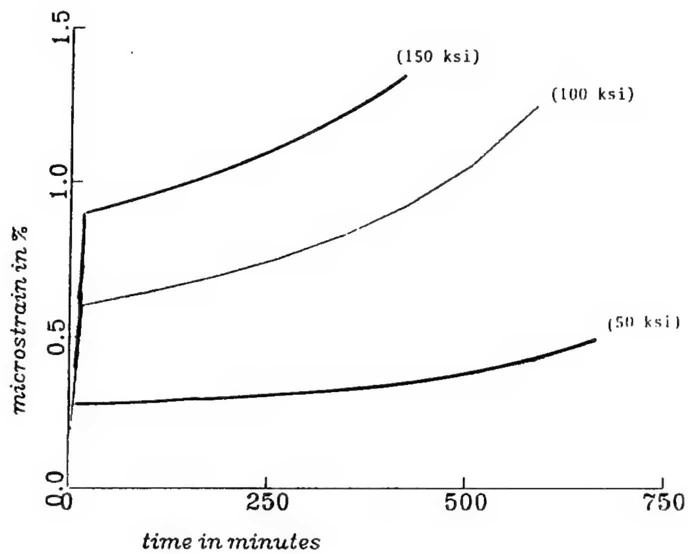
TIME-DEPENDENT PLY AND MATRIX STRAINS IN A UNIDIRECTIONAL COMPOSITE
UNDER TRANSVERSE STRESS
(SiC/Ti-15.3.3.3; 0.3 FVR; 40 ksi)



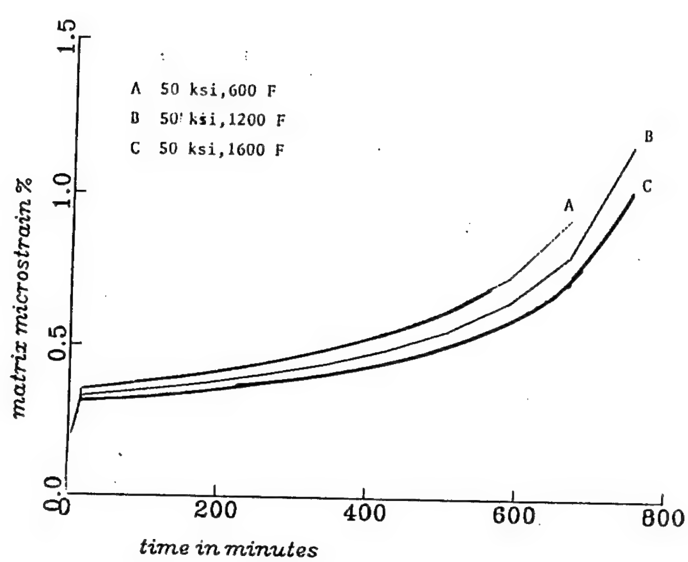
TIME-DEPENDENT PLY AND MATRIX STRAINS IN A UNIDIRECTIONAL COMPOSITE
UNDER IN-PLANE SHEAR STRESS
(SiC/Ti-15.3.3; 0.3 FVR; 50 ksi)



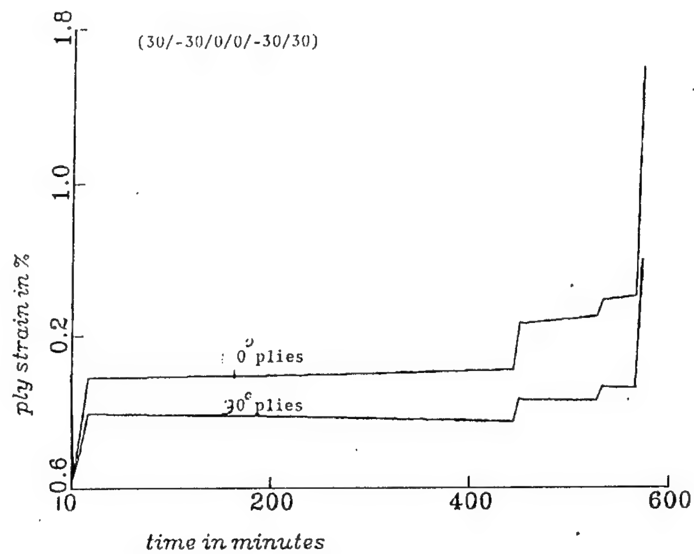
TIME-DEPENDENT MATRIX STRAIN IN A UNIDIRECTIONAL COMPOSITE UNDER DIFFERENT LONGITUDINAL STRESSES
(SiC/Ti-15.3.3.3; 0.3 FVR)



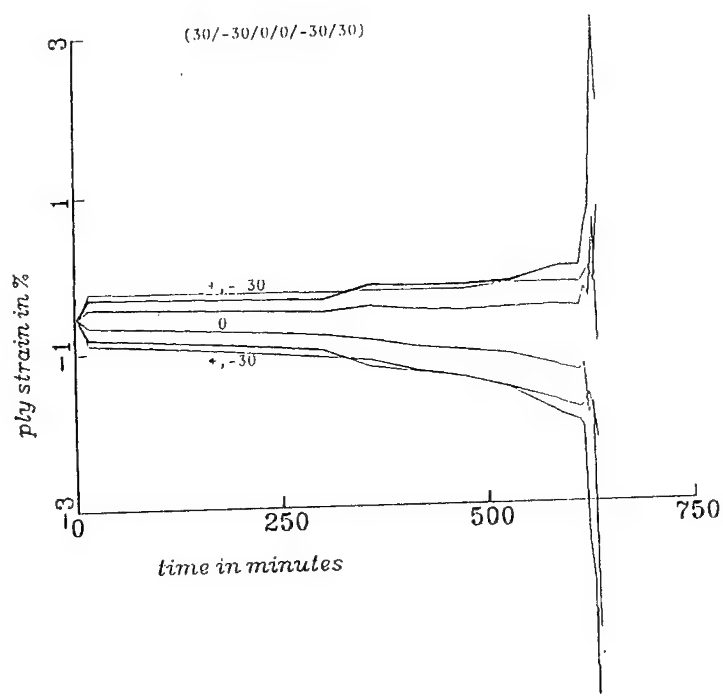
TIME-DEPENDENT MATRIX STRAINS IN A UNIDIRECTIONAL COMPOSITE SUBJECTED TO LONGITUDINAL STRESS AND DIFFERENT TEMPERATURES
(SiC/Ti-15.3.3.3; 0.3 FVR)



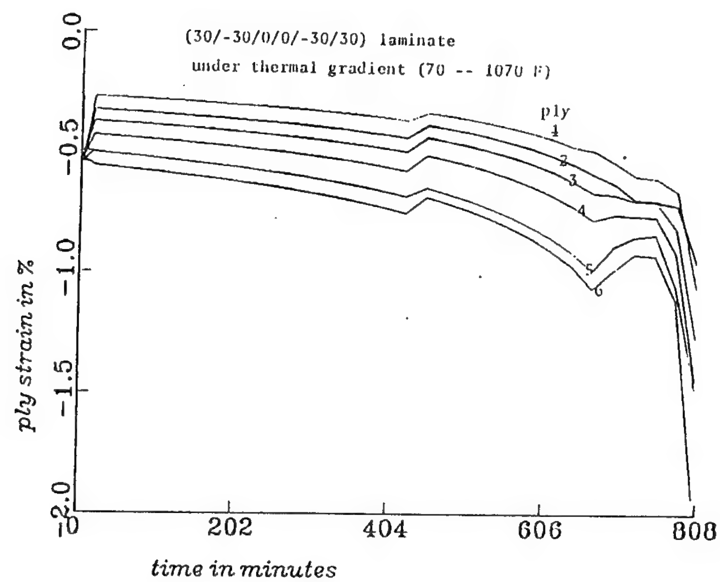
TIME-DEPENDENT PLY STRAINS IN AN ANGLEPLIED LAMINATE SUBJECTED TO LONGITUDINAL STRESS
(SiC/Ti-15.3.3.3; 0.3 FVR; 100 ksi)



TIME-DEPENDENT PLY STRAINS IN AN ANGLEPLIED LAMINATE SUBJECTED TO BENDING LOAD
(SiC/Ti-15.3.3.3; 0.3 FVR; 15 in-lb/in)



TIME-DEPENDENT PLY STRAINS OF AN ANGLEPLIED LAMINATE SUBJECTED TO THERMAL GRADIENT (SiC/Ti-15.3.3.3 at 0.3 FVR)



CONCLUSIONS:

- METCAN can be used to predict the time dependent strains in unidrectional and angle plied laminates under thermal, mechanical, and combined loading
- These strains are different in the constituents due to the presence of residual strains from the fabrication process
- Matrix becomes very sensitive to time near the final time
- The time dependence is different for different composite stresses and different temperatures as expected
- The multi-factor interaction (MFI) relationship appears to provide sufficient flexibility to accommodate the factors that influence high temperature composite behavior
- The composite restraining effects (in situ behavior) induce different time dependent behavior in the constituents than would be expected from bulk behavior
- The in situ time dependent behavior of the constituents cannot be identified from conventional uniaxial test on composites
- METCAN in conjunction with finite element structural analysis can now be used to predict time dependent behavior of composite structures

APPENDIX A: PROGRAM LISTINGS

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

INHOUSE

NONE

GRANTS AND CONTRACTS

DIRECT OBSERVATION OF CRACKING AND THE DAMAGE MECHANICS OF CERAMICS AND CERAMIC COMPOSITES
AFOSR-87-0307
01 June 87 - 31 May 90

Principal Investigator: Dr Peter W R Beaumont
Engineering Department
Cambridge University
Trumpington Street, Cambridge CB2 1PZ
(01144) 223-332600

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To directly observe and analyze microcracking and spalling in ceramic materials. To study inherent toughening methods, such as plasticity in oxide ceramics at high temperature, constrained plasticity, soft cobalt matrices, and localized transformation toughening.

STUDIES IN THE DELAMINATION FRACTURE BEHAVIOR OF COMPOSITE MATERIALS
AFOSR-84-0064
01 August 87 - 31 July 89

Principal Investigator: Dr Walter L Bradley
Department of Mechanical Engineering
Texas A&M University
College Station, TX 77843
(409) 845-1259

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To illucidate the micromechanisms underlying delamination failures in polymer composites which are subjected to mixed-mode loading.

INTERFACIAL STUDIES OF WHISKER REINFORCED CERAMIC MATRIX COMPOSITES
FQ8671-8900267
1 May 88 - 30 April 90

Principal Investigator: Dr John Brennan
United Technologies Research Center
East Hartford, CT 06108
(203) 727-7220

Program Manager: Dr Liselotte J Schioler
AFOSR/NE
Bolling AFB DC 20332-6448
(202) 767-4933

Objective: To study the microstructural and microchemical properties of interfaces of SiC and Si_3N_4 whisker reinforced glass and glass-ceramic matrix composites.

ELEVATED TEMPERATURE PERFORMANCE OF CERAMIC AND GLASS MATRIX COMPOSITES
AFOSR-87-0383
15 July 87 - 14 October 91

Principal Investigator: Professor Tsu-Wei Chou
University of Delaware
Center for Composite Materials
Newark, DE 19716
(302) 451-2904

Program Manager: Dr Liselotte J Schioler
AFOSR/NE
Bolling AFB DC 20332-6448
(202) 767-4933

Objective: To provide a fundamental understanding of the high-temperature mechanical properties, environmental effects and failure mechanisms of glass and ceramic matrix composites through experimental characterization and theoretical modeling, and to establish high-temperature mechanical testing and characterization methods for glass and ceramic matrix composites.

3D ANALYSIS AND VERIFICATION OF FRACTURE GROWTH MECHANISMS IN FIBER-REINFORCED CERAMIC COMPOSITES
AFOSR-89-0005
01 September 88 - 31 August 91

Principal Investigator: Professor Michael P Cleary
Massachusetts Institute of Technology
Cambridge, MA 02139
(617) 253-2308

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To model the fracture mechanisms in mechanical systems representative of existing and proposed ceramic composites. Emphasis is placed on the roles of the fibers and the interface in generating, arresting, or retarding the growth of fractures.

HETEROGENEOUS CHARACTERIZATION OF COMPOSITE MATERIALS WITH PROGRESSIVE DAMAGE
AFOSR-88-0124
01 February 88 - 31 January 91

Principal Investigator: Dr Isaac M. Daniel
Department of Civil Engineering
Northwestern University
Evanston, IL 60201
(312) 491-5649

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To develop constitutive and failure models for composite materials based on observed damage mechanisms and damage development. The study will include organic matrix composite materials such as graphite/epoxy, as well as high-temperature composites, such as ceramic matrix/ceramic fiber composites.

MICROCRACKING AND TOUGHNESS OF CERAMIC-FIBER/CERAMIC-MATRIX COMPOSITES UNDER HIGH TEMPERATURE
AFOSR-87-0288
01 August 87 - 30 July 89

Principal Investigators: Dr Feridun Delale
Dr Been-Ming Liaw
Department of Mechanical Engineering
The City College of
The City University of New York
New York, NY 10036
(212) 690-4252

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To study the mechanisms of microcracking at the fiber/matrix level in a ceramic-fiber/ceramic-matrix composite material subjected to thermomechanical loading.

DYNAMICS AND AEROELASTICITY OF COMPOSITE STRUCTURES
F49620-86-C-0066
01 July 86 - 30 June 90

Principal Investigator: Dr John Dugundji
Department of Aeronautics & Astronautics
Massachusetts Institute of Technology
Cambridge, MA 02139
(617) 253-3758

Program Manager: Dr Anthony K Amos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-4937

Objective: To pursue combined experimental and theoretical investigations of aeroelastic tailoring effects on flutter and divergence of aircraft wings.

DEFORMATION AND DAMAGE MECHANISMS IN HIGH TEMPERATURE COMPOSITES WITH DUCTILE MATRICES
AFOSR-88-0150
01 March 88 - 28 February 91

Principal Investigator: Dr George J Dvorak
Department of Civil Engineering
Rensselaer Polytechnic Institute
Troy, NY 12181
(518) 266-6943

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To develop a basis of understanding of the thermo-mechanical behavior of fibrous composites with ductile matrices and ductile or elasto-brittle fibers, and of the damage mechanisms activated by combined mechanical and thermal loading, both cyclic and monotonic.

COATINGS FOR FIBERS IN HIGH-TEMPERATURE, HIGH-PERFORMANCE COMPOSITES
DARPA Program
1 July 89 - 30 June 92

Principal Investigator: Professor Anthony Evans
U California, Santa Barbara
Santa Barbara, CA 93106
(805) 961-4634

Program Manager: Dr Liselotte J Schioler
AFOSR/NE
Bolling AFB DC 20332-6448
(202) 767-4933

Objective: To identify viable fiber coatings for composite systems, based on fundamental thermochemical and thermomechanical considerations, coupled with measurements made on experimental models and actual composite systems.

FAILURE OF LAMINATED PLATES CONTAINING HOLES
AFOSR-87-0204
01 April 87 - 31 March 89

Principal Investigator: Dr E S Folias
Department of Civil Engineering
The University of Utah
Salt Lake City, UT 84112
(801) 581-6931

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To analytically determine the three-dimensional stress field in a laminated plate containing a cylindrical hole through its entire thickness and loaded uniformly in the in-plane direction and to establish failure criteria.

PREDICTION AND CONTROL OF PROCESSING-INDUCED RESIDUAL STRESSES IN COMPOSITES
AFOSR-87-0242
01 June 87 - 31 May 89

Principal Investigator: Dr H Thomas Hahn
Department of Engineering Science and Mechanics
The Pennsylvania State University
University Park, PA 16802
(814) 863-0997

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To identify the mechanisms underlying the introduction of residual stresses during processing of polymer matrix composites, and to develop a prediction methodology as well as a procedure for controlling these stresses through optimization of the process cycle.

MODELING OF THE IMPACT RESPONSE OF FIBRE-REINFORCED COMPOSITES
AFOSR-87-0129
15 November 86 - 14 November 89

Principal Investigators: Dr John Harding
Dr C Ruiz
Department of Engineering Science
University of Oxford
Oxford, OX1 3PJ England

Program Manager: Dr Anthony K Amos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-4937

Objective: To characterize the mechanical behavior and failure mechanisms of carbon/epoxy, Kevlar/epoxy, and hybrid composites under tensile impact loading using specially designed split Hopkinson bar equipment.

COMPOSITE MATERIALS INTERFACE MECHANICS
AFOSR-MIPR-89-0022 (Co-funded with ONR)
01 March 89 - 28 February 91

Principal Investigator: Dr Zvi Hashin
University of Pennsylvania
Philadelphia, PA 19104-3246
(215) 898-8504

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To assess the effects of realistic interface conditions due to elastic, inelastic, and damaged interphase on the thermoelastic properties and failure of composite materials.

CRAZING IN POLYMERIC AND COMPOSITE SYSTEMS
AFOSR-87-0143
01 April 87 - 31 March 90

Principal Investigator: Dr C C Hsiao
Deparment of Aerospace Engineering and Mechanics
University of Minnesota
Minneapolis, MN 55455
(612) 625-7363

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To develop time-dependent theories for the crazing behavior of polymeric and structural composite systems by understanding the microstructural behavior of the materials during crazing.

DEVELOPMENT OF CAPABILITY FOR CHARACTERIZATION OF CERAMIC/CERAMIC COMPOSITES
F49620-89-C-0016
01 November 88 - 31 October 90

Principal Investigator: Dr Shaik Jeelani
Tuskegee Institute
Tuskegee, AL 36088
(205) 727-8970

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-4987

Objective: To devise testing methods for directly observing and characterizing damage mechanisms in fiber-reinforced ceramic composites.

STRUCTURE AND PROPERTIES OF HIGH SYMMETRY CERAMIC MATRIX COMPOSITES
AFOSR-88-0075
01 December 1987 - 30 November 1990

Principal Investigator: Professor Frank Ko
Dept of Materials Engineering
Drexel University
Philadelphia, PA 19104
(215) 895-1640

Program Manager: Dr Liselotte J Schioler
AFOSR/NE
Bolling AFB DC 20332-6448
(202) 767-4933

Objective: To determine the merit of a high symmetry hybrid architecture consisting of ceramic spheres, kevlar fibers and brittle matrix for creating tough solids by modelling, processing, optimization and mechanical properties evaluation.

THE MECHANICS OF PROGRESSIVE CRACKING IN CERAMIC MATRIX COMPOSITES AND LAMINATES
AFOSR-88-0104
01 February 88 - 31 January 91

Principal Investigator: Dr Norman Laws
Dept of Mechanical Engineering
University of Pittsburgh
Pittsburgh, PA 15261
(412) 624-9793

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To study damage processes in continuous fiber-reinforced ceramic matrix composites (CMC), and, in particular, the degradation (or improvement) of thermo-mechanical properties when the composites have been damaged by matrix cracking, fiber debonding, and ultimately fiber pull-out.

MICROMECHANICS OF INTERFACE IN HIGH-TEMPERATURE COMPOSITES
AFOSR-89-0269
01 February 89 - 31 January 92

Principal Investigator: Professor Toshio Mura
Northwestern University
Evanston, IL 60208
(312) 491-4003

Program Managers: Lt Colonel George K Haritos & Dr Liselotte J Schioler

AFOSR/NA	AFOSR/NE
Bolling AFB DC 20332-6448	Bolling AFB DC 20332-6448
(202) 767-0463	(202) 767-4933

Objective: To establish the microstructural variables which promote toughness in brittle matrix composites by means of analytical and experimental perspectives, and to construct the mechanics/material sciences based model for predicting the behavior of such materials.

OPTIMUM AEROELASTIC CHARACTERISTICS FOR COMPOSITE SUPER-MANEUVERABLE AIRCRAFT
AFOSR-89-0055
01 October 88 - 30 September 91

Principal Investigator: Dr Gabriel Oyibo
Department of Mechanical & Aerospace Engineering
Polytechnic University
Farmingdale, NY 11735
(516) 454-5120

Program Manager: Dr Anthony K Amos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-4937

Objective: To identify, characterize, and model the effects of constrained warping on the dynamics and aeroelastic stability of aircraft composite wings.

FINITE ELEMENT ANALYSIS OF COMPOSITE SHELLS
AFOSR-PD-88-0010
01 April 89 - 30 September 90

Principal Investigator: Dr Anthony Palazotto
Air Force Institute of Technology
Wright-Patterson AFB OH 45433-6583
(513) 255-2998, AUTOVON 785-2998

Program Manager: Dr Anthony K Amos
AFOSR/NA
Bolling AFB DC 20332-6448

Objective: A general nonlinear shell theory has been developed to analyze the static and dynamic characteristics of composite shells. A finite element program is being developed. Pertubation and boundary integral techniques are also being used for baseline and comparison purposes.

MESOMECHANICAL MODEL FOR FIBRE COMPOSITES: THE ROLE OF THE INTERFACE
AFOSR-89-0365
01 June 89 - 31 May 92

Principal Investigator: Professor M R Piggott
University of Toronto
Ontario, Canada M5S 1A4
(416) 978-4745

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To establish the relationship between the interface/interphase parameters and the composite properties. Particular attention is paid to the role of interphase failure.

EVOLUTION MECHANICS
AFOSR-89-0216
01 December 88 - 30 November 91

Principal Investigator: Professor K L Reifsnider
Virginia Polytechnic Institute & State University
Blacksburg, VA 24061
(703) 961-5316

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448

Objective: To develop methods for predicting the long-term behavior of composite materials, especially their remaining strength and life after periods of service which includes exposure to time-variable thermomechanical and chemical loading.

EIGENSENSITIVITY ANALYSIS OF COMPOSITE LAMINATES: EFFECT OF MICROSTRUCTURE
F49620-89-C-0003
01 November 88 - 31 October 90

Principal Investigator: Dr Robert Reiss
Howard University
Washington DC 20059
(202) 636-6608

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To assess the sensitivity of composite laminates' natural (for elastic models) and complex (for viscoelastic models) frequencies to small changes in the properties of their constituents.

MICROMECHANICAL ANALYSIS OF CERAMIC MATRIX COMPOSITES
F49620-88-C-0069
01 April 88 - 31 March 90

Principal Investigator: Dr B Walter Rosen
Materials Sciences Corporation
Gwynedd Plaza II
Bethlehem Pike
Spring House, PA
(215) 542-8400

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To develop a material model of a unidirectional composite which accounts for residual stresses, matrix porosity, interphases, cracks perpendicular to fibers, cracks parallel to fibers, interface debonding, fiber fracture, and in general, the accumulation and growth of various types of damage.

STUDIES ON DEFORMATION AND FRACTURE OF VISCOELASTIC COMPOSITE MATERIALS
AFOSR-87-0257
01 July 87 - 30 June 89

Principal Investigator: Dr Richard A Schapery
Department of Civil Engineering
Texas A&M University
College Station, TX 77843
(409) 845-2449

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To develop and verify mathematical models of deformation and delamination of viscoelastic composites with distributed micro-damages.

CONTROL AUGMENTED STRUCTURAL OPTIMIZATION OF AEROELASTICALLY TAILORED FIBER COMPOSITE WINGS
F49620-87-K-0003
01 November 86 - 31 October 89

Principal Investigators: Dr Lucien A Schmit
Dr Peretz Friedmann
Dept of Mechanical, Aerospace and Nuclear Engineering
University of California, Los Angeles
Los Angeles, CA 90024
(213) 825-7697

Program Manager: Dr Anthony K Amos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-4937

Objective: To develop a control-augmented optimization capability for the efficient aeroelastic tailoring of composite wings and lifting surfaces. The analytical methods to be developed should permit extension of formal optimization procedures in design applications beyond current capabilities.

DAMAGE ACCUMULATION IN ADVANCED METAL-MATRIX COMPOSITES UNDER THERMAL CYCLING
AFOSR-890059
15 October 88 - 14 October 91

Principal Investigator: Professor M Taya
University of Washington
Seattle, WA 98195
(206) 545-2850

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To characterize the mechanisms of the damage accumulation process in metal-matrix composites subjected to creep and/or thermal cycling, including the nucleation and growth of interface damage.

A COMPREHENSIVE STUDY ON MICROSTRUCTURE-MECHANICS RELATIONSHIPS OF CERAMIC MATRIX COMPOSITES
AFOSR-88-0113
01 April 88 - 31 March 89

Principal Investigator: Dr Albert S D Wang
Department of Mechanical Engineering and Mechanics
Drexel University
Philadelphia, PA 19104
(215) 895-2297

Program Manager: Lt Colonel George K Haritos
AFOSR/NA
Bolling AFB DC 20332-6448
(202) 767-0463

Objective: To establish both a fabrication and a material characterization capability for a class of high-temperature ceramic matrix composites as an integrated effort.

ARMY PROGRAM INPUT
Fourteenth Annual Mechanics of Composites Review

Dayton, Ohio
31 October - 1 Novemmber, 1989

submitted by
D. W. Oplinger
Army Materials Technology Laboratory
ATTN:SLCMT-MRS
Watertown MA 02172

U. S. ARMY
ARMY RESEARCH OFFICE

CONTRACTS

TITLE: Basic Research into Static and Dynamic Properties of Composite Blades with Structural Couplings
RESPONSIBLE INDIVIDUAL G. L. Anderson
Army Research Office
P. O. Box 12111
Research Triangle Park, NC 27709-2211
(919) 549-0641
PRINCIPAL INVESTIGATOR: John Dugundjii
Dept. of Aeronautics and Astronautics
Massachusetts Institute of Technology
Cambridge MA 02139

OBJECTIVE: Study analytically and experimentally the static and dynamic behavior of helicopter rotor blades made of composite materials.

TITLE: Advanced Mechanical Design of High Performance Articulating Robotic Systems
RESPONSIBLE INDIVIDUAL G. L. Anderson
Army Research Office
P. O. Box 12111
Research Triangle Park, NC 27709-2211
(919) 549-0641
PRINCIPAL INVESTIGATOR: M. V. Gandhi and B. S. Thompson
Dept. of Mechanical Engineering
Michigan State University
Ease Lansing MI 48824-1226

OBJECTIVE: Develop a new generation of high performance light weight robot arms fabricated in advanced composite materials.

TITLE: Stability of Elastically Tailored Rotor Systems
RESPONSIBLE INDIVIDUAL G. L. Anderson
Army Research Office
P. O. Box 12111
Research Triangle Park, NC 27709-2211
(919) 549-0641
PRINCIPAL INVESTIGATOR: D. Hodges and L. Rehfield
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

OBJECTIVE: Develop mathematical modeling and analysis procedures to determine the aeroelastic stability characteristics of bearingless helicopter rotors on elastic supports in axial flow and tilt rotor aircraft with elastic wings in axial flight in the helicopter mode and in the airplane mode. The rotor systems are composed of or contain significant structural components fabricated from composite materials.

TITLE: Damage Resistance in Rotorcraft Structures
RESPONSIBLE INDIVIDUAL G. L. Anderson
Army Research Office
P. O. Box 12111
Research Triangle Park, NC 27709-2211
(919) 549-0641
PRINCIPAL INVESTIGATOR: E. A. Armanios
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

OBJECTIVE: Explore the benefits of tailoring microstructure, i.e., ply stacking sequence, fiber orientation, and a blend of material plies, to contain and resist damage in rotor systems and airframe structural components. The analysis will be developed for a generic damaged ply model that includes matrix micro-cracking, delamination and fiber fracture, and their interaction.

TITLE: Optimization of Composite Drive Shafts
RESPONSIBLE INDIVIDUAL G. L. Anderson
Army Research Office
P. O. Box 12111
Research Triangle Park, NC 27709-2211
(919) 549-0641
PRINCIPAL INVESTIGATOR: M. Darlow and O. A. Bachau
Dept. of Mechanical Engineering
Renssalaer Polytechnic Institute
Troy NY 12180-3590

OBJECTIVE: Develop a computerized design process for designing composite drive shafts for rotorcraft that can operate at super-critical rotational speeds. Develop algorithms to optimize shaft systems based on geometric envelope, torsional strength and elastic stability (buckling), torsional and lateral vibrations, and weight.

TITLE: Analysis and Design of Composite Fuselage Frames
RESPONSIBLE INDIVIDUAL G. L. Anderson
Army Research Office
P. O. Box 12111
Research Triangle Park, NC 27709-2211
(919) 549-0641
PRINCIPAL INVESTIGATOR: O. A. Bachau
Dept. of Mechanical Engineering
Renssalaer Polytechnic Institute
Troy NY 12180-3590

OBJECTIVE: Develop a model that will allow the accurate analysis and design of helicopter fuselage frame components using composite materials. The features to be included are strong curvature (height to radius of curvature ratio of the order of 1 to 3), major secondary stresses (crushing and curling) due to this curvature, sharp changes in gage thickness, and material anisotropy effects including continuously varying directions of principal axes of orthotropy.

TITLE: Hygrothermal Effects on the Elastic Properties of Tailored Composite Blades
RESPONSIBLE INDIVIDUAL: G. L. Anderson
Army Research Office
P. O. Box 12111
Research Triangle Park, NC 27709-2211
(919) 549-0641
PRINCIPAL INVESTIGATOR: S. J. Winckler
Dept. of Mechanical Engineering
Rensselaer Polytechnic Institute
Troy, NY 12180-3590

OBJECTIVE: Develop analytical models for predicting changes in stiffness and coupling during hygrothermal conditioning. Perform experiments to measure such effects.

TITLE: Formal Optimization Procedures for Composite Blades
RESPONSIBLE INDIVIDUAL: G. L. Anderson
Army Research Office
P. O. Box 12111
Research Triangle Park, NC 27709-2211
(919) 549-0641
PRINCIPAL INVESTIGATOR: O. A. Bauchau
Dept. of Mechanical Engineering
Rensselaer Polytechnic Institute
Troy, NY 12180-3590

OBJECTIVE: For the full application of composite materials to rotor blades, develop design and optimization tools that allow for the imposition of multiple constraints.

TITLE: Advanced Composite Laminates for Rotorcraft
RESPONSIBLE INDIVIDUAL: G. L. Anderson
Army Research Office
P. O. Box 12111
Research Triangle Park, NC 27709-2211
(919) 549-0641
PRINCIPAL INVESTIGATOR: R. J. Diefendorff, O. A. Bauchau and S. J. Winkler
Dept. of Mechanical Engineering
Rensselaer Polytechnic Institute
Troy, NY 12180-3590

OBJECTIVE: Analytical modeling, fabrication and testing research will be undertaken to develop new two and three dimensional composite concepts that promise advanced elastic tailoring, improved load transfer and/or reduced fabrication costs. Analysis methodology will be developed that is capable of predicting the elastic characteristics of laminates with "bend" and "splay" intralaminate fiber concepts.

TITLE: Finite Element Modelling of Composite Rotor Blades
RESPONSIBLE INDIVIDUAL: G. L. Anderson
Army Research Office
P. O. Box 12111
Research Triangle Park, NC 27709-2211
(919) 549-0641
PRINCIPAL INVESTIGATOR: S. Lee and A. Vizzini
Dept. of Aerospace Engineering
University of Maryland
College Park, MD 20742

OBJECTIVE: Develop a beam finite element formulation of the combined dynamic bending, torsional, and extensional behavior of composite rotor blades taking into account the warping effect of blades undergoing large deflection or finite rotation. This new approach models thin walled composite blades with complicated cross sections, tapers, and arbitrary planforms. The warping effect is incorporated by assuming warping displacements superimposed over cross sections normal to the beam axis in the deformed configuration of a shear-flexible beam. Numerical tests of simple static problems demonstrate the validity and effectiveness of this approach.

TITLE: Vibration Control and Optimization in Composite Structural elements by Use of Add-on Damping Materials
RESPONSIBLE INDIVIDUAL: G. L. Anderson
Army Research Office
P. O. Box 12111
Research Triangle Park, NC 27709-2211
(919) 549-0641
PRINCIPAL INVESTIGATOR: C. T. Sun and P. Hajela
Dept. of Aerospace Engineering
University of Florida
Gainesville, FL 32611
OBJECTIVE: Develop techniques of vibration control through add-on damping for structures fabricated from composite materials. Apply optimization techniques for the purpose of determining the optimum structural/damping treatment design.

TITLE: Manufacturing Science, Reliability and Maintainability Technology **RESPONSIBLE INDIVIDUAL**: A. Crowson

Army Research Office
P. O. Box 12111
Research Triangle Park, NC 27709-2211
(919) 549-0641

PRINCIPAL INVESTIGATORS: T. W. Chou and R. L. McCullough
Center For Composite Materials
University of Delaware
Newark DE 19716

OBJECTIVE: This University Research Initiative Program consists of the following elements : cure characterization and monitoring, on-line intelligent non destructive evaluation for in-process control of manufacturing, process simulation, computer aided manufacturing by filament winding, structural property relationships, mechanics of thick section composite laminates, structure performance and durability and integrated engineering for durable structures.

U. S. ARMY LABORATORY COMMAND
MATERIALS TECHNOLOGY LABORATORY

TITLE: Composite Hull for Light Infantry Fighting Vehicle
PROJECT ENGINEER: W. Haskell
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5172
PRINCIPAL INVESTIGATOR: E. Weerth
FMC Corp.
San Jose, CA

OBJECTIVE: Demonstrate the application of thick composites technology to armored vehicles for the purpose of weight reduction. Payoffs in the form of reduced weight, over aluminum for equal ballistic protection, reduced spall, elimination of corrosion, signature reduction, reduced life cycle costs and logistic improvements related to easier transportability and lowered fuel consumption, are being demonstrated.

TITLE: Lightweight Towbar for Battlefield Recovery
PROJECT ENGINEER: G. Piper
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5745
PRINCIPAL INVESTIGATOR: G. Samavedam
Foster-Miller Inc.
350 Second Ave.
Waltham, MA 02254

OBJECTIVE: The objective of this effort is demonstration of the ability of composites to replace steel for weight reduction in tow bars used for battlefield recovery of the M1 tank and similar heavy vehicles. Scope includes design, fabrication and demonstration of a selected towbar design. Combinations of glass and graphite reinforced materials using filament winding and braiding manufacturing approaches are under study.
Battlefield ruggedness of the composite towbar is an overriding consideration in judging the success of the program.

TITLE: Design Analysis of Composite Test Specimens
PROJECT ENGINEER: D. W. Oplinger
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5303
PRINCIPAL INVESTIGATOR: S. Chaterjee
Materials Sciences Corp.
Gwynedd Plaza II
Bethlehem Pike
Spring House PA
(215) 542-8400

OBJECTIVE: The objective is to evaluate current specimen designs for mechanical-property test specimens for composites and to develop design improvements. Effort includes combined stress analysis effort to evaluate specimen designs of interest, and experimental effort to provide confirmatory data, both for evaluation of current specimens and assessment of suggested improvements. Mechanical tests of interest include compression, in plane shear, interlaminar shear and tension.

TITLE: Lightweight Howitzer Project
RESPONSIBLE INDIVIDUAL: A. Johnson
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5427
PRINCIPAL INVESTIGATOR: D. W. Oplinger
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5303

OBJECTIVE: The objective of this effort is to demonstrate the application of composite materials to towed artillery, for the purpose of weight reduction. Available air transport facilities for many of the Army's operating units do not allow the transport of weapons of sufficient effectiveness because of the weight of such weapons. Scope of the effort includes design, fabrication and demonstration of various howitzer components to provide confidence in the ability of such materials to provide battlefield ruggedness.

TITLE: Failure and Degradation of Adhesive Joints
RESPONSIBLE INDIVIDUAL: A. Johnson
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5427
PRINCIPAL INVESTIGATOR: D. Oplinger
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5259

OBJECTIVE: The objective is to provide the Army with improved design, life prediction and reliability methodology for adhesive joints. The effort includes analytical and experimental efforts aimed at investigating:(1) development of improved analytical methods for fracture of adhesive joints, including adhesive bond failures as well as cohesive failures in composite adherends;(2) application of moire interferometry to evaluating pre-cracked bending specimens for adhesive testing;(3) provision of an up-to-date assessment of joint stress analysis and design methodology; (4) development of methodology for 3-D modelling of joints;(5) investigation of environmental degradation effects;(6) development of improved finite element approaches for modelling adhesive joints.

TITLE: Computational Mechanics of Thick Composites
RESPONSIBLE INDIVIDUAL: A. Johnson
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5427
PRINCIPAL INVESTIGATOR: A. Tessler
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5356

OBJECTIVE: The program objective is to develop analytic methods for predicting mechanical response and failure of advanced thick composite structures which may involve stress concentrators such as cutouts, fasteners, delaminations and defects. The analytic development is facilitated by a comprehensive experimental verification involving modal analysis and moire methods. The program approach encompasses: (1) development of an effective and yet simple higher-order laminated composite shell theory which would be amenable to finite element modeling to simulate linear and nonlinear dynamic response; (2) development of reliable and efficient finite element models for the analysis of composite shell structures and adhesively bonded composite joints; (3) experimental validation of the analytic and computational models via modal analysis and moire strain methods. The technology will improve the design methods for Army's thick composite structures such as those employed in helicopter rotor blades, tank hulls and turrets, light-weight howitzers, kinetic energy projectiles, and a whole range of other applications.

TITLE: Experimental Displacement Contouring of Pin Loaded Plates

RESPONSIBLE INDIVIDUAL: A. Johnson
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5427

PRINCIPAL INVESTIGATOR: S. Serabian
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5260

OBJECTIVE: The objective of this work unit is to apply conventional moire methodologies to pinloaded laminates to obtain both inplane and out of plane displacement components. A displacement contouring load history of fiberglass epoxy 0/90, +45/-45, and 0/90/+45/-45 laminates will be undertaken. Recent advances in data analysis will be employed to obtain full field strain surfaces from these experimental displacement contours thus providing an experimental data base for comparisons with on-going 3D finite element modeling activities. The effects of laminate orientation upon mechanical response will be investigated.

TITLE: Three Dimensional Finite Element Modelling of Pin Loaded Laminates

RESPONSIBLE INDIVIDUAL: A. Johnson
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5427

PRINCIPAL INVESTIGATOR: S. Serabian
U.S. Army Laboratory Command
Materials Technology Laboratory
Watertown, MA 02172-0001
(617) 923-5260

OBJECTIVE: The objective of this work unit is to model 0/90, +45/-45, and 0/90/+45/-45 pinloaded laminates and obtain 3D finite element approximations to their mechanical response. Both linear elastic and nonlinear elastic approximations will be undertaken. Three dimensional constitutive equations will be derived from a 2D lamina characterization of the fiber-resin system and application of laminate theory. Laminate tensile and 3 point bending tests will be conducted to obtain transverse shear and through thickness Poison ratio properties. Comparisons to ongoing experimental displacement contouring activities will highlights the effects of material linearity modeling assumptions.

TITLE: Dynamics of Structures

RESPONSIBLE INDIVIDUAL: R. Shufford
U.S. Army Materials Technology Laboratory
ATTN: SLCMT-MEC
Watertown, MA 02172
(617) 923-5572

PRINCIPAL INVESTIGATORS: G.E. Foley, J. McMorrow, M.E. Roylance
U.S. Army Materials Technology Laboratory
ATTN: SLCMT-MEC
Watertown, MA 02172
(617) 923-5514

OBJECTIVE: The objective of this program is the development of modal analysis as a predictive technique for detection of damage in composite structures, such as foam core sandwich panels. This is done by characterizing the structure in terms of its modal parameters. Changes in the damping, natural frequencies, as well as the mode shapes are investigated as a function of damage in composite structures.

TITLE: Effect of Fabrication Variables on Composite Structures
RESPONSIBLE INDIVIDUAL: R. Shufford
U.S. Army Materials Technology Laboratory
ATTN: SLCMT-MEC
Watertown, MA 02172
(617) 923-5572
PRINCIPAL INVESTIGATORS: G.E. Foley, S. Ghiorse, M.E. Roylance
U.S. Army Materials Technology Laboratory
ATTN: SLCMT-MEC
Watertown, MA 02172
(617) 923-5514

OBJECTIVE: The objective of this program is to determine the advantages and/or disadvantages of different manufacturing techniques, such as braiding, filament winding, and hand lay-up on the mechanical properties, as well as the environmental durability of these composites.

TITLE: Automated Evaluation of Composite Materials
RESPONSIBLE INDIVIDUAL: G.L. Hagnauer
U.S. Army Materials Technology Laboratory
ATTN: SLCMT-EMP
Watertown, MA 02172-0001
PRINCIPAL INVESTIGATORS: G.L. Hagnauer and S.G.W. Dunn
Polymer Research Branch
U.S. Army Materials Technology Laboratory
(617) 923-5121

OBJECTIVES: The objectives of this project are to increase laboratory productivity and improve the quality of test information needed to evaluate fiber-reinforced polymeric matrix composite materials and guide their specification, design and manufacture. Laboratory robotics and artificial intelligence (AI) technologies are being developed to meet requirements for handling and testing large numbers of specimens under a wide range of conditions and to increase the efficiency and reduce labor costs involved in evaluating composite materials. To control automation and deal with the large amounts of information generated by automated testing, advanced computer and AI technologies (e.g., expert systems, image analysis and machine learning) are being implemented. AI techniques will be employed to advise and plan tests, control robots and automated test equipment, and interpret and preserve information in a living database and as reports with fully traceable documentation. Currently, the technology is being implemented in research on the durability evaluation and life prediction of composites.

TITLE: Dynamic characterization of Advanced Materials
RESPONSIBLE INDIVIDUAL: J. Nunes
U.S. Army Materials Technology Laboratory
ATTN: SLCMT-MRM-MTG
Watertown, MA 02172-0001
(617) 923 5554
PRINCIPAL INVESTIGATORS: W. Crenshaw
U.S. Army Materials Technology Laboratory
ATTN: SLCMT-MRM-MTG
Watertown, MA 02172-0001
(617) 923 5203

OBJECTIVE: Design and evaluate instrumentation systems and experimental designs to measure load response of advanced composites and homogeneous materials to low speed impact loading. Conduct standard material evaluations to determine residual strength oaf the material after impact. Determine the accuracy if present constitutive models in predicting the dynamic behavior of composites and homogeneous materials during low speed impact.

TITLE: Ultrasonic Digital Signal Processing(DSP)

RESPONSIBLE INDIVIDUAL: A. Broz
U.S. Army Materials Technology Laboratory
ATTN: SLCMT-MRM
Watertown, MA 02172-0001
(617) 923 5285

PRINCIPAL INVESTIGATORS: B. Taber
U.S. Army Materials Technology Laboratory
ATTN: SLCMT-MRM
Watertown, MA 02172-0001
(617) 923 5443

OBJECTIVE: Digital Signal Processing(DSP) is a computer based technique for enhancement of digital signals related to image processing. DSP techniques are being developed that enhance ultrasonic inspection capabilities in conjunction with NDE of composites and other applications. For example, DSP can provide additional information about individual plies in thin-lamina composites. It has also been used for the evaluation of thin bondlines in adhesive bonds. NDE efforts at MTL will emphasize the use of DSP in conjunctions with ultrasonic B scans which have been used for void location, volume fraction determination and imaging of the layered structure of laminates.

U. S. ARMY LABORATORY COMMAND
BALLISTIC RESEARCH LABORATORY

TITLE: Composite Structures

PRINCIPAL INVESTIGATOR: W.H. Drysdale
AMC LABCOM
Ballistic Research Laboratory
Aberdeen Proving Ground
MD 240055066
(301) 278-6132

OBJECTIVE: The objective of this project is to develop failure criteria, architecture transition technology, and optimum design technology for thick ballistic structures. Rate of loading and layup transition studies are being addressed at BRL. A special, high-rate, propellant driven test apparatus is under development to generate uniaxial or triaxial stress states at strain rates of up to 200 per second. Three dimensional failure criteria and other constitutive effects are being studied and hypothesized by Lawrence Livermore National Lab(LLNL). They are also sponsoring studies at the University of Utah and Pennsylvania State University. Experimental activities to develop failure data are being conducted at both the LLNL and the University of Utah. Additional failure criteria work and extensions to optimal notions for relatively simple structures and layup.

U. S. ARMY MISSILE COMMAND

TITLE: Determination of Mechanical Material Properties for Filament Wound Structures
RESPONSIBLE INDIVIDUAL: Dr. Larry C. Mixon
Army Missile Command
PRINCIPAL INVESTIGATOR: Terry L. Vandiver
Army Missile Command
(205) 876-1015

OBJECTIVE: The objective of this task is to develop test standards for the determination of mechanical material properties for filament wound composite structures. The initial task is to develop uniaxial material properties. Future plans include biaxial and triaxial material property determination. This effort is being performed by the Joint-Army-Navy-NASA-Air Force (JANNAF) Composite Motor Case Subcommittee through a round robin test effort. This task is coordinated with MIL-HDBK-17, ASTM, National Bureau of Standards, and DoD CMPS Composites Technology Program.

TITLE: Composite Materials Evaluation for Filament Winding
RESPONSIBLE INDIVIDUAL: Lawrence W. Howard
Army Missile Command
PRINCIPAL INVESTIGATOR: Terry L. Vandiver
Army Missile Command
(205) 876-1015

OBJECTIVE: The object of this task is to evaluate new fibers for filament winding. Delivered strengths are determined via strand tests and 3-inch diameter filament wound pressure vessels with different stress ratios. The experimental data is used in the design of composite rocket motor cases, launchers, pressure vessels and other filament wound structures.

TITLE: Composite Wing Design and Fabrication
RESPONSIBLE INDIVIDUAL: Lawrence W. Howard
Army Missile Command
PRINCIPAL INVESTIGATORS: J. Frank Wlodarski
Terry L. Vandiver
Army Missile Command
(205) 876-0398

OBJECTIVE: The objective of this task is to design and fabricate an all composite wing with an elliptical planform. The materials used are s-glass cloth and uni-directional tape. These materials were selected because of their strength, stiffness and low radar cross-section. The method of fabrication is hand layup in a clamshell mold made of composite tooling. The wings are tested to determine what structural properties are achieved with this method of manufacture and if they are accurately predicted in the design.

TITLE: Evaluation of Finite Element Codes
RESPONSIBLE INDIVIDUAL: Lawrence W. Howard
Army Missile Command
PRINCIPAL INVESTIGATORS: David McNeill and J. Frank Wlodarski
Army Missile Command
(205) 876-0398

OBJECTIVE: The principal objectives of this evaluation were to find a commercially available PC based finite element code that can be utilized with little training. The main specifications that the codes were evaluated against were user friendliness of the pre and post processors, clarity of user manuals, accuracy of results and ability to handle composite structures.

U. S. ARMY AVIATIONS SYSTEMS COMMAND
FT. EUSTIS

TITLE: Damage Tolerance Testing of the ACAP Roof
RESPONSIBLE INDIVIDUAL: F. Swats
U.S. Army ARTA (AVSCOM)
Aviation Applied Technology Directorate
SAVRT-TY-ATS
Ft. Eustis, VA 23604-5577
(804) 878-2975
PRINCIPAL INVESTIGATOR: B. Spigel

OBJECTIVE: A forward roof subcomponent from the Bell Advanced Composite Airframe Program (ACAP) helicopter will be tested to verify the damage tolerance design criteria developed under contract by Bell Helicopter Textron, Inc. (Final Report: USAAVSCOM TR-87-D-3A, B, C). The roof will be subjected to an anticipated ACAP load spectrum, and manufacturing defects and in-service damage will be monitored by both laboratory and field nondestructive evaluation methods to determine the extent of damage growth.

TITLE: Ballistic Survivability of Generic Composite Main Rotor Hub Flexbeams
RESPONSIBLE INDIVIDUAL: F. Swats
U.S. Army ARTA (AVSCOM)
Aviation Applied Technology Directorate
SAVRT-TY-ATS
Ft. Eustis, VA 23604-5577
(804) 878-2975
PRINCIPAL INVESTIGATORS: E. Robeson and K. Sisitka

OBJECTIVE: The goal of this effort is to quantify the ballistic survivability of typical composite main rotor hub flexbeams. Two different flexbeam designs will be impacted with various ballistic threats. One design will be tested under simulated centrifugal load while the other will be fatigue tested following ballistic impact in a no load condition. Fatigue testing of the first design will be considered after a damage assessment is made.

TITLE: Finite Element Correlation of the Advanced Composite Airframe Program (ACAP Dynamic Models
RESPONSIBLE INDIVIDUAL: E. Austin
U.S. Army ARTA (AVSCOM)
Aviation Applied Technology Directorate
SAVRT-TY-ATS
Ft. Eustis, VA 23604-5577
(804) 878-3822
PRINCIPAL INVESTIGATORS: N. Calapodas and D. Kinney
U.S. Army ARTA (AVSCOM)
Aviation Applied Technology Directorate
SAVRT-TY-ATS
Ft. Eustis, VA 23604-5577
(804) 878-3303

OBJECTIVE: A joint program among Army/NASA/Contractor is planned to conduct detail correlation of the Finite Element (FE) dynamic models of both ACAP airframes. AATD will perform all shake testing and the contractors will be responsible for analytical changes to the FE models. The FE dynamic models, generated under Army funding during the develop-mental phase of the ACAP program, were further improved under funding of the NASA DAMVIBS program. However, the thrust of shake testing performed during the developmental phase was oriented towards qualifying the flightworthy vehicles for flight testing rather than conducting detail correlation of the FE models. The results obtained from the limited shake testing identified substantial discrepancies between test and analysis, limiting the usefulness of the models to 15 Hz and below. In the correlation to be performed, the test vehicles will be stripped down to the basic structure. The inertia of the components removed will be substituted with

concentrated masses. Upon successful correlation of the basic configuration, components will be installed and correlation efforts repeated. The goal is to achieve satisfactory correlation at modal and force response frequencies up to 40 Hz.

TITLE: Composite Airframe Design for Weapons Interface
RESPONSIBLE INDIVIDUAL: E. Austin
U.S. Army ARTA (AVSCOM)
Aviation Applied Technology Directorate
SAVRT-TY-ATS
Ft. Eustis, VA 23604-5577
(804) 878-3822
PRINCIPAL INVESTIGATORS: J. Moffatt
U.S. Army ARTA (AVSCOM)
Aviation Applied Technology Directorate
SAVRT-TY-ATS
Ft. Eustis, VA 23604-5577
(804) 878-2377
OBJECTIVE: The effect of 20-30mm weapon firing in close proximity to composite airframe is investigated. Effects of weapon-induced pressure and thermal environments on weight tradeoffs for structural design are investigated.

U. S. ARMY AVIATIONS SYSTEMS COMMAND
US ARMY RESEARCH & TECHNOLOGY ACTIVITY
NASA-LANGLEY RESEARCH CENTER

TITLE: Basic Research in Structures
RESPONSIBLE INDIVIDUAL: Dr. F. D. Bartlett, Jr.
U.S. Army ARTA
Aerostructures Directorate
Mail Stop 266
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3960
PRINCIPAL INVESTIGATORS: Dr. T.K. O'Brien, Dr. R.L. Boitnott, G.L. Farley, M.W. Nixon

OBJECTIVE: The objectives and scope of this research are to investigate and explore structures technologies which exploit advanced materials for improved structural performance, develop superior analyses for composites design, and devise automated processes for inspecting and manufacturing rotorcraft structures. This is accomplished, in conjunction with NASA Langley, by conducting basic research of composite and metallic materials to understand and improve fatigue resistance, fracture toughness, crashworthiness, and internal noise transmission as well as to develop more efficient and damage tolerant structural forms for rotorcraft applications.

TITLE: Structures Technology Applications
RESPONSIBLE INDIVIDUAL: Dr. F.D. Bartlett, Jr.
U.S. Army ARTA
Aerostructures Directorate
Mail Stop 266
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3960
(804) 865-2866
PRINCIPAL INVESTIGATORS: Dr. R.L. Boitnott, M.W. Nixon, G.L. Farley, D.J. Baker

OBJECTIVE: The goals of this research are to explore and demonstrate innovative structural concepts and design methodologies which will provide lighter, safer, and more survivable structures for rotorcraft. This is achieved through jointly-sponsored Army/NASA investigations which establish improved structural integrity and crashworthiness, validate superior analytical capabilities, and demonstrate lower c[illegible] manufacturing processes. The emphasis of this research is to provide proven technology to the rotorcraft industry and the U.S. Army for applications to future air vehicle systems.

OFFICE OF NAVAL RESEARCH
MECHANICS DIVISION
ARLINGTON VA 22217-5000

FAILURE OF THICK COMPOSITE LAMINATES
N00014-88-F-0044
February 88 - January 90

Scientific Officer: Dr Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Dr R. M. Christensen
Lawrence Livermore National Laboratory
PO Box 808
Livermore CA 94550
(415) 422-7136

Objective: Research will be conducted into the mechanics of failure of composite materials, with emphasis on physically-based failure criteria for thick composite laminates.

NONDESTRUCTIVE EVALUATION AND DAMAGE ACCUMULATION OF COMPOSITES
N00014-87-K-0159
April 87 - December 91

Scientific Officer: Dr Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof I. M. Daniel
Northwestern University
Department of Civil Engineering
Evanston IL 60201
(312) 491-5649

Objective: Research will be conducted to understand the process of damage growth in composite laminates subjected to complex loading states and fatigue. Methods for damage characterization will be developed. The effects of damage on macroscopic properties of stiffness, strength and fatigue life will be established.

ENVIRONMENTAL EFFECTS AND ENVIRONMENTAL DAMAGE IN COMPOSITES
N00014-82-K-0562
October 84 - September 90

Scientific Officer: Dr Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof Y. Weitsman
Texas A&M University
Department of Civil Engineering
College Station TX 77843
(409) 845-7512

Objective: Research will be conducted into the effects of stress, temperature and moisture on the mechanical response of polymer composties. Environmentally induced damage growth and its effect on composite response will be investigated.

DYNAMIC MATRIX CRACKING AND DELAMINATION IN COMPOSITE LAMINATES SUBJECTED TO IMPACT LOADING
N00014-84-K-0554
July 84 - October 91

Scientific Officer: Dr Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof C. T. Sun
Purdue University
School of Aeronautics and Astronautics
West Lafayette IN 47907
(317) 494-5130

Objective: The propagation of damage in composite laminates due to impact loading conditions will be investigated using theoretical and experimental techniques. Dynamic delamination models will be established. Concepts for controlling impact damage will be explored.

THERMOMECHANICAL BEHAVIOR OF HIGH TEMPERATURE COMPOSITES
N00014-85-K-0247
March 85 - July 91

Scientific Officer: Dr Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof G. J. Dvorak
Rensselaer Polytechnic Institute
Department of Civil Engineering
Troy NY 12181
(518) 276-6943

Objective: Investigations of the thermomechanical response, damage growth and fracture in intermetallic matrix composites will be conducted using analytical and experimental techniques. Local stress states caused during fabrication and by thermal changes in service, in elastic time-dependent behavior, and static and fatigue damage will be explored.

QUANTITATIVE ULTRASONICS MEASUREMENTS IN COMPOSITES
N00014-85-K-0460
July 85 - September 92

Scientific Officer: Dr Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof W. Sachse
Cornell University
Department of Theoretical and Applied Mechanics
Ithaca NY 14853
(607) 255-5065

Objective: Research will be conducted to establish quantitative active and passive ultrasonic measurement techniques for characterizing the microstructure and mechanical properties as well as the dynamics of deformation processes in a variety of composite materials.

DYNAMIC BEHAVIOR OF FIBER AND PARTICLE REINFORCED COMPOSITES
N00014-86-K-0280
October 86 - September 90

Scientific Officer: Dr Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof S. K. Datta
University of Colorado
Department of Mechanical Engineering
Boulder CO 80309
(303) 492-1139

Objective: Research will be conducted into the diffraction of elastic waves by cracks and other inhomogeneities in laminated fiber reinforced composites. Investigations of dynamic material properties of fiber and particle reinforced metal-matrix composites will be conducted.

IMPACT RESPONSE AND QNDE OF LAYERED COMPOSITES
N00014-87-K-0351
April 87 - December 91

Scientific Officer: Dr Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof A. K. Mal
University of California, Los Angeles
Department of Mechanical, Aerospace and Nuclear Engineering
Los Angeles CA 90024
(213) 825-5481

Objective: Research will be conducted into wave propagation in composite laminates, with the focus on dynamic loading conditions and theoretical aspects of quantitative acoustic microscopy. The Leaky Lamb Wave technique will be utilized for the characterization of elastic properties and defects in composites. The use of ultrasonic techniques for interfaces and interfacial regions will be explored.

MICROMECHANICS OF COMPOSITES
N00014-84-K-0510
June 84 - September 91

Scientific Officer: Dr Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof B. Budiansky
Harvard University
Division of Applied Science
Cambridge MA 02138
(617) 495-2849

Objective: Research will be conducted into the micromechanical enhancement of the fracture toughness of ceramics and intermetallics by the incorporation of toughening agents such as fibers, whiskers, ductile particles, and phase-transforming particles.

MECHANICS OF INTERFACE CRACKS
N00014-88-K-0119
November 87 - September 91

Scientific Officer: Dr Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof C. F. Shih
Brown University
Division of Engineering
Providence RI 02912
(401) 863-2868

Objective: Research will be conducted to provide a fundamental understanding of the behavior of interface cracks in bimaterial elastic-plastic systems. The stress and strain fields around such cracks will be studied at both the continuum and polycrystalline slip theory levels.

FRACTURE MECHANICS OF INTERFACIAL ZONES IN BONDED MATERIALS
N00014-89-J-3188
September 89 - August 91

Scientific Officer: Dr Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Prof F. Erdogan
Lehigh University
Department of Mechanical Engineering and Mechanics
Bethlehem PA 18015
(215) 758-3020

Objective: Research will be conducted into the micromechanics aspects of failure of composites, accounting for realistic interfacial zones. Models will be established for crack propagation in interfacial regions with continuously varying mechanical properties.

3D SYNCHROTRON X-RAY MICROTOMOGRAPHY FOR COMPOSITES
N00014-89-C-0076
April 89 - March 90

Scientific Officer: Dr Yapa D. S. Rajapakse
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington VA 22217-5000
(202) 696-4405, Autovon 226-4405

Principal Investigator: Dr A. S. Krieger
Radiation Science, Inc
PO Box 293
Belmont MA 02173
(617) 494-0335

Objective: The nondestructive technique of three dimensional synchrotron x-ray microtomography will be used for the assessment of internal structure and defects in composite materials and composite interfaces.

NATIONAL CENTER FOR COMPOSITE MATERIALS RESEARCH
p400013f101
September 86 - September 91

Scientific Officer: Dr R. F. Jones
Office of Naval Research
Mechanics Division, Code 1132-SM
Arlington VA 22217-5000
(202) 696-4305, Autovon 226-4305

Principal Investigator: Prof S. S. Wang
University of Illinois
Department of Theoretical and Applied Mechanics
Urbana IL 61801
(217) 333-1835

Objective: Under ONR-URI sponsorship, a National Center for Composite Materials Research was established to conduct a well structured, multidisciplinary research program in composites spanning the disciplines of solid mechanics, materials science, chemistry and surface physics. Initial emphasis will be on critical research issues associated with the use of thick composites for ship structures.

NAVAL RESEARCH LABORATORY
WASHINGTON, DC 20375-5000
CONTRACTS

DYNAMIC BEHAVIOR OF COMPOSITES
N00014-86-C-2580
October 86 - March 90

Scientific Officer: Mr Irvin Wolock
Naval Research Laboratory
Washington DC 20375-5000
(202) 767-2567, Autovon 297-2567

Principal Investigator: Dr Longin B. Greszczuk
McDonnell Douglas Astronautics Company
5301 Bolsa Avenue
Huntington Beach CA 92647
(714) 896-3810

Objective: Establish the response of composite materials subjected to large area dynamic loading from underwater explosions.

NAVAL AIR DEVELOPMENT CENTER
WARMINSTER PA 18974-5000
IN-HOUSE

HYBRID COMPOSITE FRACTURE CHARACTERIZATION
September 85 - October 89

Project Engineer: Lee W. Gause
Naval Air Development Center
AVCSTD/6043
Warminster PA 18974-5000
(215) 441-1330, Autovon 441-1330

Objective: Characterize the strength, mechanical properties, and damage tolerance of woven and hybrid composite structures.

STRUCTURAL DAMPING
October 87 - September 90

Project Engineer: Dr D. J. Barrett
Naval Air Development Center
AVCSTD/6043
Warminster PA 18974-5000
(215) 441-1330, Autovon 441-1330

Objective: Improve the damping properties of structures through the redesign of basic structural components as composites of stiffness and damping materials.

ANALYTICAL MODELING OF COMPOSITE INTERFACE MECHANICS
April 88 - September 90

Project Engineer: Lee W. Gause
Naval Air Development Center
AVCSTD/6043
Warminster PA 18974-5000
(215) 441-1330, Autovon 441-1330

Objective: Understand how interface failure mechanisms develop and influence the properties of resin matrix composites and devise non-linear micromechanics models to describe the behavior at the interface region.

METAL MATRIX CRACK INITIATION/PROPAGATION
September 85 - October 89

Project Engineer: Dr H. C. Tsai
Naval Air Development Center
AVCSTD/6043
Warminster PA 18974-5000
(215) 441-2871, Autovon 441-2871

Objective: Characterize the crack initiation/propagation mechanics of silicon carbide/titanium metal matrix composites as applied to landing gear and arrestor hooks in the naval shipboard environment.

CONTRACTS

OUT-OF-PLANE ANALYSIS FOR COMPOSITE STRUCTURES
N62269-87-C-0226
September 87 - September 89

Project Engineer: E. Kautz
Naval Air Development Center
AVCSTD/6043
Warminster PA 18974-5000
(215) 441-1561, Autovon 441-1561

Principal Investigator: C. R. Saff
McDonnell Aircraft Company
Box 516
St Louis MO 63166
(314) 233-8623

Objective: To develop and verify an analysis methodology that provides an up-front capability to identify potential out-of–plane loading situations in composite structures and determine strength and failure mode without resorting to expensive three dimensional finite element analysis.

DAVID TAYLOR RESEARCH CENTER
BETHESDA MD 20084-5000
ANNAPOLIS MD 21842
IN-HOUSE

COMPRESSION RESPONSE OF THICK-SECTION COMPOSITE MATERIALS
October 86 - September 91

Principal Investigator: E. T. Camponeschi, Jr.
David Taylor Research Center, Code 2844
Annapolis MD 21842
(301) 267-2165, Autovon 281-2165

Objective: Develop an understanding of compression failure for thick section composites.

BEHAVIOR OF COMPOSITES SUBJECTED TO UNDERWATER EXPLOSIVE LOADING
January 87 - September 90

Principal Investigator: Erik Rasmussen
David Taylor Research Center, Code 1720
Bethesda MD 20084-5000
(301) 227-1656, Autovon 287-1656

Objective: Develop the analytical and experimental techniques required to assess the dynamic capabilities of proposed composite submarine pressure hull structural and material concepts.

COMPOSITE PRESSURE HULL PENETRATION AND JOINT DESIGN
June 88 - September 90

Principal Investigator: M. Brown
David Taylor Research Center, Code 1720.2
Bethesda MD 20084-5000
(301) 227-1706, Autovon 287-1706

Objective: Develop structurally efficient joint, penetration, and reinforcement concepts for composite pressure hulls; the analytical capability to predict the structural response of these concepts; the experimental capability to verify the validity of the analytical procedures.

COMPOSITE STRUCTURES FOR SURFACE SHIPS
October 85 - September 93

Principal Investigator: M. Critchfield
David Taylor Research Center, Code 1730.2
Bethesda MD 20084-5000
(301) 227-1769, Autovon 287-1769

Objective: Develop the basic technology to support the applications of composites to naval ship structures including design and analytic methods in structural joints and attachments, and to demonstrate the feasibility of using FRP composites for surface ship structural applications such as deckhouses, stacks and masts, and secondary structures.

NASA LANGLEY RESEARCH CENTER

IN-HOUSE

ADVANCED CONCEPTS FOR COMPOSITE HELICOPTER FUSELAGE STRUCTURES
83 April 1 - 92 January 1

Project Engineer: Mr. Donald J. Baker
Mail Stop 190
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3171 FTS 928-3171

Objective: To investigate new design concepts for composite materials on lightly loaded helicopter fuselage structures. Trade studies will be performed using the various computer codes. A 4-year task assignment contract was awarded in Fiscal Year 1989 to fabricate selected designs that will be tested at NASA Langley.

POSTBUCKLING AND CRIPPLING OF COMPRESSION-LOADED COMPOSITE STRUCTURAL COMPONENTS
79 March 1 - 90 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Objective: To study the postbuckling and crippling of compression-loaded composite components and to determine the limitations of postbuckling design concepts in structural applications.

DESIGN TECHNOLOGY FOR STIFFENED CURVED COMPOSITE PANELS AND SHELLS
79 October 1 - 90 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Objective: To develop verified design technology for generic advanced-composite stiffened curved panels.

POSTBUCKLING OF FLAT STIFFENED GRAPHITE/EPOXY SHEAR WEBS
81 July 1 - 90 September 30

Project Engineer: Mr. Marshall Rouse
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3182 FTS 928-3182

Objective: To study the postbuckling response and failure characteristics of flat stiffened graphite/epoxy shear webs.

POSTBUCKLING ANALYSIS OF GRAPHITE/EPOXY LAMINATES
80 October 1 - 90 September 30

Project Engineer: Dr. Manuel Stein
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3179 FTS 928-3179

Objective: To develop accurate analyses for the postbuckling response of graphite/epoxy laminates and to determine the parameters that govern postbuckling behavior.

CRASH CHARACTERISTICS OF COMPOSITE FUSELAGE STRUCTURES
82 July 1 - 89 September 30

Project Engineer: Mr. Huey D. Carden
Mail Stop 495
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4151 FTS 928-4151

Objective: To study the crash characteristics of composite transport fuselage structural components.

BUCKLING AND STRENGTH OF THICK-WALLED COMPOSITE CYLINDERS
86 October 1 - 90 September 30

Project Engineer: Ms. Dawn C. Jegley
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3185 FTS 928-3185

Objective: To develop accurate analyses for the buckling and strength predictions of thick-walled composite cylinders.

ADVANCED COMPOSITE STRUCTURAL CONCEPTS
84 October 1 - 92 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Objective: To develop composite structural concepts and design technology needed to realized the improved performance, structural efficiency, and lower-cost advantage offered by new material systems and manufacturing methods for advanced aircraft structures.

FAILURE MECHANISMS FOR COMPOSITE LAMINATES WITH DAMAGE AND LOCAL DISCONTINUITIES
76 October 1 - 90 September 30

Project Engineer: Dr. Mark J. Shuart
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3170 FTS 928-3170

Objective: To study the effects of impact damage and local discontinuities on the strength of composite structural components, to identify the failure modes that govern the behavior of components subjected to low-velocity impact damage, and to analytically predict failure and structural response.

MECHANICS OF ANISOTROPIC COMPOSITE STRUCTURES
86 October 1 - 90 September 30

Project Engineer: Dr. Michael P. Nemeth
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3184 FTS 928-3184

Objective: To develop analytical procedures for anisotropic structural components that accurately predict the response for tailored structures.

COMPOSITES CHARACTERIZATION WORK BREAKDOWN STRUCTURE
1975 - Present

Project Engineer: Dr. Joseph S. Heyman
IRD, Nondestructive Measurement Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4970 FTS 928-4970

Objective: Develop quantitative measurement and technology to characterize properties of composites nondestructively and link physical properties thus measured to engineering properties needed for materials and structures certification.

QUANTITATIVE MEASUREMENTS OF MATERIALS PROPERTIES
1985 May.-1992 Sept.

Project Engineer: Dr. Eric Madaras
IRD, Nondestructive Measurement Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, Va. 23665-5225
(804) 864-4993 FTS 928-4993

Objective: The objective of this work is to develop advanced measurement systems for improved nondestructive characterization of composite materials. Recent work has included quantitative evaluations of porosity and other material defects in composites and the measurement of moduli in carbon-carbon composites..

IMAGE ENHANCEMENT TECHNIQUES FOR QUANTITATIVE EVALUATION STUDIES OF COMPOSITE MATERIALS
1986 June - 1990 September

Project Engineer: Dr. Patrick H. Johnston
IRD, Nondestructive Measurement Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4966 FTS 928-4966

Objective: To combine quantitative techniques of measurement science with methods of image production, enhancement, and display to aid in the nondestructive characterization and evaluation of composite structures.

DEVELOP NDE MEASUREMENT TECHNIQUES TO DETERMINE STATE OF FATIGUE FOR AEROSPACE MATERIALS
1988 September - 1993 September

Project Engineer: Dr. William T. Yost
IRD, Nondestructive Measurement Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4991 FTS 928-4991

Objective: To compare engineering-based fatigue properties with other physical measurements (including microstructural characteristics) in metals.

DEVELOP COMPOSITE MATERIALS WITH EMBEDDED FIBER-OPTIC SENSORS FOR IN-SITU MONITORING OF MATERIAL PROPERTIES
1988 September - 1991 September

Project Engineer: Dr. Robert S. Rogowski
IRD, Nondestruction Measurement Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4990 FTS 928-4990

Objective: Investigate fiber-optic sensors as potential internal sensors for composite materials. The embedded sensors are intended to monitor cure processing and subsequently serve as sensors for strain, temperature, physical and chemical damage, and other parameters important to the function of the material during use.

USE OF ULTRASONIC TECHNIQUES FOR COMPOSITE CURE MONITORING AND CHARACTERIZATION OF RESIN SYSTEM DURING PROCESSING
1983 September - 1990 September

Project Engineer: Dr. William P. Winfree
IRD, Nondestructive Measurement Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4963 FTS 928-4963

Objective: The objective of this program is to develop techniques for determining the material properties of composites during their cure. These material properties can be used as input to a process controller which can tailor a process to maximize the integrity of a composite. The research has concentrated on using ultrasonic techniques, with both conventional transducers and acoustic wave guides as sensors.

QUANTITATIVE ACOUSTIC EMISSION ANALYSIS OF ADHESIVE BOND FAILURE

Project Engineer: Mr. William H. Prosser
IRD, Nondestructive Measurement Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4960 FTS 928-4960

Objective: The objective is to study the influence of fracture toughness of the adhesive, mode of fracture, and crack velocity on the acoustic emission released during adhesive bond failure.

DEVELOPMENT OF ANALYTICAL MODELS OF THE THERMOMECHANICAL BEHAVIOR OF METAL MATRIX COMPOSITES
87 June - 90 September 30

Project Engineer: Dr. C. A. Bigelow
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3462 FTS 928-3462

Objective: To develop finite-element codes, laminate-analysis codes, and micromechanics models necessary to analytically investigate mechanics issues related to the fatigue, fracture, and thermomechanical behavior of MMC's.

DELAMINATION MICROMECHANICS ANALYSIS
85 October 1 - 90 September 30

Project Engineer: Dr. John H. Crews, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3457 FTS 928-3457

Objective: To develop 2-D a fiber-resin stress analysis for region near a delamination front containing microcracks.

MECHANICS MODELS OF 3-D ADVANCED COMPOSITE FORMS
88 June 1 - 89 September 30

Project Engineer: Dr. Charles E. Harris
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3449 FTS 928-3449

Objective: To develop mechanics-based models of the deformation and local stress states that reflect the local fiber curvature of 3-D advanced composite forms. These models will form the basis for establishing strength (failure) criteria and will provide insight into an optimized material form from the mechanics viewpoint. Experiments will be conducted to support the model development and to verify predictions.

EXPERIMENTAL AND ANALYTICAL CHARACTERIZATION OF THE MECHANICAL BEHAVIOR OF METAL MATRIX COMPOSITES
80 June - 90 September 30

Project Engineer: Dr. W. Steven Johnson
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3463 FTS 928-3463

Objective: To experimentally investigate the fatigue, fracture, and thermomechanical behavior of MMC's to insure airframe structural integrity at elevated temperatures. Both continuously reinforced laminates and discontinuous particulate and whisker reinforced MMC's will be included in the study.

INTERLAMINAR SHEAR FRACTURE TOUGHNESS
89 May - 90 September 30

Project Engineer: Ms. Gretchen B. Murri
Mail Stop 188E
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3466 FTS 928-3466

Objective: Cyclic end-notched flexure tests will be used to measure the mode II strain energy release rate of two materials in fatigue. Results will be used to develop ASTM test standards for strain energy release rate under fatigue loading.

DELAMINATIONS IN TAPERED COMPOSITE LAMINATES WITH INTERNAL PLY DROPS
88 October - 90 September 30

Project Engineer: Ms. Gretchen B. Murri
Mail Stop 188E
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3466 FTS 928-3466

Objective: To characterize delamination failures in tapered composites containing internal ply-drops. Experimental results from a variety of materials and lay-ups will be compared with finite element and closed-form solutions.

DELAMINATION GROWTH IN TAPERED COMPOSITE LAMINATES WITH INTERNAL PLY DROPS
89 September 30 - 92 September 30

Project Engineer: Dr. T. Kevin O'Brien
Mail Stop 188E
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3465 FTS 928-3465

Objective: In tapered composites containing internal ply drops which undergo tension and bending loads, delamination failures are typically observed at the locations of the ply drops. The objective of this program is to develop analyses which accurately model this delamination failure mode.

INTERLAMINAR FRACTURE TOUGHNESS TESTING OF COMPOSITES
86 April - 90 September 30

Project Engineer: Dr. T. Kevin O'Brien
Mail Stop 188E
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3465 FTS 928-3465

Objective: In order to develop standard tests for measuring interlaminar fracture toughness of composites, ASTM Committee D30 on High Modulus Fibers and Their Composites has organized a round robin series of four test methods. The double cantilevered beam (DCB), edge delamination tension (EDT), cracked lap shear (CLS) and end-notched flexure (ENF) tests will be evaluated by a total of 32 laboratories using 3 different materials, ranging from very brittle to very tough.

STUDY OF DAMAGE TOLERANCE OF THERMOPLASTIC COMPOSITES
88 December - 92 December

Project Engineer: Mr. C. C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3467 FTS 928-3467

Objective: To develop an analysis that can also be used as a design tool for predicting the complete damage state during and after impact and the residual properties in thermoplastic and thermoset matrices.

IMPACT RESPONSE AND DAMAGE IN THREE-DIMENSIONAL BRAIDED GRAPHITE FIBER COMPOSITES
87 October - 90 October

Project Engineer: Mr. C. C. Poe, Jr.
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3467 FTS 928-3467

Objective: To characterize damage in three-dimensional braided composites subjected to hard object impact at low energy levels.

MIXED-MODE DELAMINATION TESTING
87 September 1 - 90 September 30

Project Engineer: Mr. James R. Reeder
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3456 FTS 928-3456

Objective: To measure the delamination fracture toughness of laminated composites material subjected to combined mode I and mode II loadings and thereby develop a mixed mode delamination failure criterion. The new mixed-mode-bending specimen will be used for testing.

EXPERIMENTAL EVALUATION OF ADVANCED COMPOSITE MATERIAL FORMS

84 June 1 - 90 June 1

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3094 FTS 928-3094

Objective: To determine mechanical properties and establish damage tolerance of 2-D and 3-D woven, stitched, and braided composite materials.

FLIGHT SERVICE EVALUATION OF COMPOSITE COMPONENTS ON COMMERCIAL AND MILITARY AIRCRAFT
72 March 1 - 90 December 31

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3094 FTS 928-3094

Objective: To evaluate the long-term durability of composite components installed on commercial and military transport and helicopter aircraft. Over 300 components constructed of boron, graphite, and Kevlar composites will be evaluated after extended service. Components include graphite/epoxy rudders, spoilers, tail rotors, vertical stabilizers, Kevlar/epoxy fairings, doors and ramp skins, and boron/aluminum aft pylon skins. Note: Over 4.5 million total component flight hours have been accumulated since initiation of flight service in 1972. Composite components on L-1011, B-737, and DC-10 aircraft have accumulated over 40,000 flight hours each. Excellent in-service performance and maintenance experience has been achieved with the composite components.

MICROMECHANICS MODELING OF COMPOSITE THERMOELASTIC BEHAVIOR
86 October - 90 June 30

Project Engineer: Mr. David E. Bowles
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3095 FTS 928-3095

Objective: Develop analytical methods to investigate thermally induced deformations and stresses in continuous fiber-reinforced composites at the micromechanics level, and predict how these deformations and stresses affect the dimensional stability of the composite.

THERMAL DEFORMATIONS AND STRESSES IN COMPOSITE/HONEYCOMB PANELS FOR PRECISION REFLECTORS
89 June 1 - 91 May 31

Project Engineer: Mr. David E. Bowles
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3095 FTS 928-3095

Objective: Analytically and experimentally investigate the effects of constituent properties (fiber, matrix, honeycomb, adhesive) on thermally induced deformations and stresses in composite honeycomb panels for precision reflector applications.

ADVANCED COMPOSITE MATERIALS FOR ULTRA-HIGH PRECISION REFLECTOR HONEYCOMB PANELS
88 October 1 - 91 September 30

Project Engineer: Dr. Stephen S. Tompkins
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3096 FTS 928-3096

Objective: Develop advanced structural composite materials that are dimensionally stable and durable in the LEO and GEO space environments. These materials will form facesheets of honeycomb panels used to construct precision reflector panels for space applications. A critical requirement for the facesheet materials is to replicate a highly polished, very accurate mold surface (surface accuracy about 3 microns RMS).

THERMAL AND MECHANICAL STABILITY OF COMPOSITE MATERIALS
83 October 1 - 93 September 30

Project Engineer: Dr. Stephen S. Tompkins
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3096 FTS 928-3096

Objective: Develop and evaluate structural composite materials (resin-, metal-, and glass-matrix) that are dimensionally stable and/or have stable thermal and mechanical properties when subjected to simulated long-term LEO and GEO space service environments.

FAILURE ANALYSIS AND DAMAGE TOLERANCE OF COMPOSITE AIRCRAFT STRUCTURES
NAS1-17925
85 February 23 - 90 September 30

Project Engineer: Dr. Mark J. Shuart
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3170 FTS 928-3170

Principal Investigator: Dr. R. K. Kunz
Lockheed Aeronautical Systems Co.
Burbank, CA 91520
(818) 847-7995

Objective: To develop advanced structural concepts and to advance the analytical capability to predict composite structural failure.

ANISOTROPIC SHELL ANALYSIS
NAG-1-901
88 October 1 - 90 September 30

Project Engineer: Dr. Michael P. Nemeth
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3184 FTS 928-3184

Principal Investigator: Dr. Michael W. Hyer
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
(703) 231-5372

Objective: To develop accurate analyses for the response of anisotropic composite shell structures.

THICKNESS DISCONTINUITY EFFECTS
NAG-1-537
85 October 1 - 90 September 30

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Principal Investigator: Dr. Eric R. Johnson
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
(703) 231-6126

Objective: To develop verified analytical models of compression loaded laminates with thickness discontinuities and dropped plies.

MECHANICS OF ANISOTROPIC STRUCTURES WITH CUTOUTS
NAG-1-917
88 December 1 - 89 December 1

Project Engineer: Dr. Michael P. Nemeth
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3184 FTS 928-3184

Principal Investigator: Dr. E. C. Klang
North Carolina State University
Raleigh, NC 27695
(919) 737-2365

Objective: To develop efficient analytical procedures that accurately predict the response of anisotropic structural components with cutouts.

STRUCTURAL DESIGN CRITERIA FOR FILAMENT-WOUND COMPOSITE SHELLS
NAG-1-982
89 May 15 - 90 May 15

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Principal Investigator: Dr. H. T. Hahn
Pennsylvania State University
University Park, PA 16802
(814) 865-4523

Objective: To develop structural design criteria that can be used to scale-up filament wound composite shells.

COMPOSITE FUSELAGE TECHNOLOGY
NAG-1-982
89 April 7 - 90 April 7

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Principal Investigator: Dr. P. A. Lagace
Massachusetts Institute of Technology
Cambridge, MA 02139
(617) 253-3628

Objective: To conduct experimental and analytical studies of pressurized composite fuselage shells subjected to damage.

FIBER BUCKLING IN LAMINATED PLATES
NAG-1-1040
89 October 1 - 90 September 30

Project Engineer: Dr. Mark J. Shuart
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3170 FTS 928-3170

Principal Investigator: Dr. A. Waas
University of Michigan
Ann Arbor, MI 48109-1248
(313) 764-8227

Objective: Conduct experimental and analytical studies to isolate and observe in-situ failure mechanisms for composite structures.

FIBER WAVEGUIDE SENSORS FOR INTELLIGENT MATERIALS
NAG-1-895
1988 September - 1990 October

Project Engineer: Dr. Robert S. Rogowski
IRD, Nondestructive Measurement Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4990 FTS 928-4990

Principal Investigator: Richard O. Claus
Department of Electrical Engineering
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061

Objective: Development of fiber-optic based opto-electronic sensing instrumentation for the characterization of materials and structures.

QUANTITATIVE NONDESTRUCTIVE EVALUATION OF COMPOSITE MATERIALS BASED ON ULTRASONIC WAVE PROPAGATION
NSG-1-601
1981 September - 1990 September

Project Engineer: Dr. Eric Madaras
IRD, Nondestructive Measurement Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4993 FTS 928-4993

Principal Investigator: Dr. James G. Miller
Department of Physics
Washington University
St. Louis, MO 33130

Objective: The overall goal of our research program is the development and application of quantitative ultrasonic techniques to problems of nondestructive evaluation of composites materials. One goal of this work is to demonstrate the potential application of approaches base on the relationship between frequency dependent attenuation and dispersion to nondestructive evaluation of porosity. A second goal is the use of quantitative polar backscatter and attenuation measurements to characterize material properties.

CONTRACTS

COLLAPSE AND FAILURE MODES IN ADVANCED COMPOSITE STRUCTURES
NSG-1483
78 January 15 - 90 January 14

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Principal Investigator: Dr. Wolfgang G. Knauss
California Institute of Technology
Pasadena, CA 91125
(213) 356-4524/4528

Objective: To experimentally and analytically study time-dependent effects on buckling and failure of composite structures with discontinuities.

ADVANCED COMPOSITE STRUCTURAL DESIGN TECHNOLOGY FOR COMMERCIAL TRANSPORT AIRCRAFT
NAS1-15949
79 September 24 - 90 March 23

Project Engineer: Dr. James H.Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Principal Investigator: Mr. R. E. Barrie
Lockheed Aeronautical Systems Co.
Burbank, CA 91520
(818) 847-9997

Objective: To design, analyze, fabricate, and test generic advanced-composite structural components for transport aircraft applications in order to develop verified design technology.

STRUCTURAL OPTIMIZATION FOR IMPROVED DAMAGE TOLERANCE
NAG-1-168
81 September 1 - 90 October 15

Project Engineer: Dr. James H. Starnes, Jr.
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3168 FTS 928-3168

Principal Investigator: Dr. Raphael T. Haftka
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
(703) 231-4860

Objective: To develop a structural optimization procedure for composite wing boxes that includes the influence of damage-tolerance considerations in the design process.

INVESTIGATION OF ACOUSTIC PROPERTIES OF COMPOSITE MATERIALS
NAG-1-431
1983 September - 1990 September

Project Engineer: Dr. Eric Madaras
IRD, Nondestructive Measurement Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4993 FTS 928-4993

Principal Investigator: Dr. Barry T. Smith
Department of Physics
Christopher Newport College
Newport News, VA 23606

Objective: The research involves an investigation of the ultrasonic acoustic properties of composite materials. The objective is to characterize the material as well as develop means of assessing any damage. Research to date has included quantitative measurement of impact damage in thin graphite/epoxy composites, evaluation of porosity and determination of fundamental ultrasonic properties to elucidate the propagation of ultrasonic waves in these materials.

NONDESTRUCTION EVALUATION OF CARBON-CARBON COMPOSITES
1989 September - 1995 September

Project Engineer: Dr. Eric Madaras
IRD, Nondestructive Measurement Science Branch
Mail Stop 231
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4993 FTS 928-4993

Principal Investigator: Dr. Ron Kline
Aerospace and Mechanical Engineering
University of Oklahoma
Norman, OK 73019

Objective: The research involves methods of measuring the elastic moduli of carbon-carbon material and integrating the results with FEM codes to predict the behavior of components. Also, research related to nondestructive evaluation of carbon-carbon coatings will be investigated.

CRACK PROBLEMS IN ORTHOTROPIC PLATES AND NONHOMOGENEOUS MATERIALS
NAG-1-713
86 November 1 - 90 October 31

Project Engineer: Dr. C. A. Bigelow
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3462 FTS 928-3462

Principal Investigator: Dr. Fazil Erdogan
Department of Mechanical Engineering and Mechanics
Lehigh University
Bethlehem, PA 18015
(215) 758-4099

Objective: The objective of this program is the study of plate and shell structures containing surface cracks under mixed mode loading conditions, the consideration of crack closure on the compression side of plate with a through crack under bending, the determination of the profile of a subcritically growing crack in a plate under bending and membrane loading, and the modeling of the interface region in bonded materials.

MICROMECHANICS OF COMPOSITE LAMINATE COMPRESSIVE FAILURE
NAG-1-659
86 February 1 - 90 June 30

Project Engineer: Dr. Charles E. Harris
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3449 FTS 928-3449

Principal Investigator: Dr. Walter Bradley
Department of Mechanical Engineering
Texas A&M University
College Station, TX 77843

Objective: The objective of this program is to characterize the compressive failure behavior of notched laminates under static and sustained loads. Both room temperature and elevated temperature conditions are being examined.

THERMAL VISCOPLASTICITY IN METAL MATRIX COMPOSITES
L-24457C
87 July - 90 January

Project Engineer: Dr. W. S. Johnson
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3463 FTS 928-3463

Principal Investigator: Dr. Yehia A. Bahei-El-Din
Department of Civil Engineering
Rensselaer Polytechnic Institute
Troy, NY 12180-3590
(518) 276-8043

Objective: This contract is to develop an analytical method for estimating thermal viscoplasticity stresses and strains in continuous fiber-reinforced metal matrix composites due to fabrication and/or subsequent thermal cycling and mechanical loadings.

ANALYSIS OF INTERLAMINAR FRACTURE IN COMPOSITES UNDER COMBINED LOADING
NAG-1-637
89 October 1 - 90 September 30

Project Engineer: Ms. Gretchen B. Murri
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Mail Stop 188E
Hampton, VA 23665-5225
(804) 864-3466 FTS 928-3466

Principal Investigator: Dr. E. A. Armanios
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332

Objective: The objective of this program is to extend an existing sublaminate analysis method to model tapered ply-drop configurations under bending and combined tension-bending loads. The analyses are intended for use on personal-class computers.

DEVELOPMENT OF ADVANCED WOVEN COMPOSITE MATERIALS AND STRUCTURAL FORMS
NAS1-18358
86 August 29 - 90 August 29

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3094 FTS 928-3094

Principal Investigator: Ms. Janice Maiden
Textile Technologies, Inc.
2800 Turnpike Drive
Hatboro, PA 19040
(215) 443-5325

Objective: To develop textile technology to produce 2-D and 3-D woven preforms and structural elements with integral stiffening, multilayers, and multidirectional reinforcement.

ANALYSIS OF 2-D AND 3-D REINFORCED COMPOSITES
NAS1-18000
87 March 1 - 90 September 30

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3094 FTS 928-3094

Principal Investigator: Mr. Raymond L. Foye
Mail Stop 188B
PRC Kentron, Inc.
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3093 FTS 928-3093

Objective: To develop analytical methods to understand and predict the elastic and strength response of 2-D and 3-D reinforced composite materials. Emphasis is on improved fracture toughness and impact resistance for woven, stitched, and braided material forms.

ENVIRONMENTAL EXPOSURE EFFECT ON COMPOSITE MATERIALS FOR COMMERCIAL AIRCRAFT
NAS1-15148
77 November 1 - 90 December 31

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3094 FTS 928-3094

Principal Investigator: Mr. Randy Coggeshall
Boeing Commercial Airplane Company
P.O. Box 3707
Seattle, WA 98124
(206) 234-6695

Objective: To provide technology in the area of environmental effects on graphite/epoxy composite materials, including long-term performance of advanced resin-matrix composite materials in ground and flight environments.

MECHANICAL PROPERTIES OF 3-D WOVEN FABRIC
NCC-1-130
88 August 1 - 90 August 1

Project Engineer: Mr. Gary L. Farley
Mail Stop 188B
Aerostructures Directorate, USAARTA (AVSCOM)
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3091 FTS 928-3091

Principal Investigator: Dr. John M. Kennedy
Department of Mechanical Engineering
Clemson University
Clemson, SC
(803) 656-5632

Objective: Establish the mechanical response and damage tolerance characteristics of 3-D woven fabrics.

VISCOELASTIC RESPONSE OF COMPOSITE/HONEYCOMB PANELS FOR PRECISION REFLECTORS
NAG-1-343
88 August 16 - 90 July 31

Project Engineer: Mr. D. E. Bowles
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3095 FTS 928-3095

Principal Investigator: Dr. M. W. Hyer
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061
(703) 961-5372

Objective: Analytically and experimentally investigate the viscoelastic response of sandwich panels fabricated from composite facesheets and honeycomb cores.

UNIT CELL GEOMETRY OF COMPLEX PREFORMS FOR STRUCTURAL COMPOSITES
NCC-1-138
89 May 1 - 92 May 1

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3094 FTS 928-3094

Principal Investigator: Drs. Christopher M. Pastore and Frank K. Ko
Department of Materials Engineering
Drexel University
Philadelphia, PA 19104
(215) 895-1844

Objective: Develop computerized graphics models for a variety of 2-D and 3-D textile fiber architectures for use in micromechanics analysis. Unit cells will be defined and a library of these cells can be used in fabric analysis or finite element models for stress analysis.

THERMALLY INDUCED INTERFACIAL STRESS-STRAIN BEHAVIOR IN RESIN MATRIX COMPOSITES
NAS1-18231
87 August 1 - 88 July 31

Project Engineer: Mr. D. E. Bowles
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3095 FTS 928-3095

Principal Investigator: Dr. B. N. Cox
Rockwell Science Center
P.O. Box 1085
Thousand Oaks, CA 91360
(805) 373-4287

Objective: Experimentally and analytically investigate the thermally induced interfacial stress-strain behavior in aerospace resin matrix composites.

ADVANCED COMPOSITE FABRICATION AND TESTING
NAS1-18954
89 August - 94 August

Project Engineer: Mr. Marvin B. Dow
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3090 FTS 928-3090

Principal Investigator: Mr. Anthony Falcone
Boeing Aerospace
Seattle, WA 98124
(206) 234-2678

Objective: . process and test experimental composite materials and state-of-the-art systems including woven, braided, knitted, and stitched fiber forms. Processing shall include resin transfer molding, pultrusion, and thermoforming.

DEVELOPMENT OF FILAMENT WINDING PROCESS FOR GR/TP COMPOSITE LAMINATES
NAS1-18624
89 April 27 - 90 April 27

Project Engineer: Mr. J. W. Deaton
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3087 FTS 928-3087

Principal Investigator: Mr. G. E. Walker, Jr.
Hercules Aerospace Company
Composite Products Group
Bacchus Works
Magna, UT 84044-0098
(801) 251-4194

Objective: Development of consolidation processes for Gr/TP filament-wound/fiber-placement laminates and demonstration of laminate quality through nondestructive evaluation/inspection and mechanical testing. Machining of specimens from Gr/TP laminates and all mechanical testing will be accomplished at NASA Langley.

ADVANCED COMPOSITE STRUCTURAL CONCEPTS AND MATERIAL TECHNOLOGIES FOR PRIMARY AIRCRAFT STRUCTURES
NAS1-18888
1989 April - 1995 May

Project Engineer: Dr. Mark J. Shuart
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3170 FTS 928-3170

Principal Investigator: Mr. A. Jackson
Lockheed Aeronautical Systems Company
Department 7007
Building 369, Plant B6
Burbank, CA 91520
(818) 847-5450

Objective: To develop and verify innovative structural concepts such as geodesic stiffening, sandwich construction, and pultruded stiffeners that exploit the full potential of integrated design/manufacturing procedures to achieve light-weight and cost-effective primary structures; and to develop a strong structural mechanics technology base to predict the performance of advanced concepts.

NOVEL MATRIX RESINS WITH IMPROVED PROCESSABILITY AND PROPERTIES FOR PRIMARY AIRCRAFT STRUCTURES
NAS1-18841
1989 April - 1992 April

Project Engineer: Dr. P. Hergenrother
Mail Stop 226
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4270 FTS 928-4270

Principal Investigator: Dr. E. P. Woo
Dow Chemical Company
1712 Building
Midland, MI 48674
(517)-636-1072

Objective: Develop new high performance thermoset resins with improved durability, toughness and processability. The resins will be targeted for aircraft structural applications with maximum use temperatures ranging from 180°F to 450°F. New resins including vinyl esters, cyanates, modified epoxies, acetylene-terminated polymers and bisbenzocyclobutenes will be synthesized. The suitability of the new resin technology for use in resin transfer molding as well as for conventional prepreg processing will be evaluated.

ADVANCED MATERIALS AND PRODUCT FORMS
NAS1-18834
1989 April - 1995 May

Project Engineer: Dr. N. Johnston
Mail Stop 188M
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3493 FTS 928-3493

Principal Investigator: Mr. J. T. Hartness
BASF
13504-A South Point Blvd.
Charlotte, NC 28217
(704)-588-7976

Objective: Develop improved matrix resins and unique material forms that offer increased performance and improved processability over state-of-the-art structural composite materials. Two prepreg concepts will be developed and evaluated. The first will use either thermoplastic or thermoset polymer powders to impregnate fiber tows or woven preforms. The second will employ thermoplastics spun into fibers and intimately blended with the reinforcing fibers.

EFFECTS OF MATRIX AND INTERPHASE ON CARBON FIBER COMPOSITE COMPRESSION STRENGTH
NAS1-18883
1989 April - 1995 May

Project Engineer: Dr. Jeff Hinkley
Mail Stop 226
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-4259 FTS 928-4259

Principal Investigator: Dr. Willard D. Bascom
M.S. 304 EMRO
University of Utah
Salt Lake City, UT 84112
(801)-581-7422

Objective: Determine the material parameters that control composite compression strength, so that the fiber/matrix/interphase combination can be optimized. At least four commercial carbon fibers, five fiber coatings, and several epoxy matrix resins having different moduli will be studied. In each case, individual fiber failure modes will be characterized using in-situ microscopy and post-failure etching techniques. Next, propagation of damage in small bundles of fibers and in individual plies will be examined using specially-constructed specimens. Finally, the translation of these effects to strengths of laminate coupons and to multiaxial tension-compression behavior of tube structures will be determined.

CHARACTERIZING THE FRACTURE TOUGHNESS OF ADVANCED COMPOSITE STRUCTURES
NAS1-18833
1989 April - 1995 May

Project Engineer: Dr. John Crews
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3457 FTS 928-3457

Principal Investigator: Dr. John A. Nairn
M.S. 304 EMRO
University of Utah
Salt Lake City, UT 84112
(801) 581-3413

Objective: Develop fracture mechanics analyses for predicting matrix microcracks and microcrack-induced delaminations. Conduct tests to identify the parameters that govern microcracking and microcrack-induced delaminations. Then, develop strain energy release rate (G) analyses for observed damage initiation modes and growth modes. Finally, interpret composite stiffness degradation and fracture toughness in terms of critical strain energy release rates for damage initiation and growth.

THE MICROMECHANICS OF FATIGUE FAILURE IN WOVEN AND STITCHED COMPOSITES
NAS1-18840
1989 April - 1995 May

Project Engineer: Dr. Charles E. Harris
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3449 FTS 928-3449

Principal Investigator: Dr. Brian Cox
P.O. Box 1085
Rockwell International
1049 Camino Dos Rios
Thousand Oaks, CA 91360
(805)-373-4128

Objective: Develop experimental techniques to characterize the initiation and growth of fatigue damage. Determine the effect of damage on the internal stresses and the global composite stiffness. Based on damage characterization, develop micromechanical model for predicting fatigue behavior of new material architectures.

DAMAGE TOLERANCE OF COMPOSITE PLATES
NAS1-18778
1989 April - 1995 May

Project Engineer: Mr. C. C. Poe
Mail Stop 188E
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3467 FTS 928-3467

Principal Investigator: Dr. G. S. Springer
Department of Aeronautics and Astronautics
Stanford University
Stanford, CA 94305
(415)-723-4135

Objective: Develop an analysis to predict the complete damage state during and after low-velocity impact and to predict the residual properties. The analysis will be sufficiently general to account for the unique properties of thermoplastic matrix materials while applying to other matrices as well. A three-dimensional finite element model will be developed to calculate stresses, strains, and displacements in a composite during impact based on Hertzian contact forces. The model will define impactor position, velocity, and force as a function of time and will be general regarding material properties and composite layup. The model will predict fiber and matrix damage and trace delamination growth. The analysis will be verified through impact tests wherein the impact force and the extent of damage will be measured. Both destructive and nondestructive techniques will be used to determine the extent of damage.

ADVANCED FIBER PLACEMENT FUSELAGE TECHNOLOGY PROGRAM
NAS1-18887
1989 April - 1995 May

Project Engineer: Mr. W. T. Freeman
Mail Stop 241
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-2945 FTS 928-2945

Principal Investigator: R. L. Anderson
M.S. X11K4
Hercules Incorporated
P.O. 98
Magna, Utah 84044
(801)-251-2077

Objective: To develop breakthrough technology for cost effective fabrication of damage tolerant composite fuselage structures. A six-axis tow placement technique will be used to achieve low cost manufacturing of highly efficient complex structural forms. Major emphasis shall be on innovative manufacturing methods that may offer options for highly efficient primary aircraft structures. Six 3 x 4-ft flat isogrid panels will be fabricated using 8551-7/IM-7 damage tolerant material and subjected to a variety of static tests with and without damage. Following flat panel qualification in Phase 1, three full scale 5 x 6-ft curved panels will be fabricated and tested for concept verification.

INNOVATIVE FABRICATION PROCESSING OF ADVANCED COMPOSITE MATERIALS CONCEPTS FOR PRIMARY AIRCRAFT STRUCTURE
NAS1-18799

1989 May 9 - 1992 August 9

Project Engineer: Mr. J. W. Deaton
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-30870 FTS 928-3087

Principal Investigator: Mr. S. P. Garbo
United Technologies
Sikorsky Aircraft Division
6900 Main Street
Stratford, Conn. 06601-1381
(203)-386-4576

Objective: Develop unique and innovative design concepts for complex fuselage structure that are amenable to the Therm-X pressure molding fabrication process. Concept drivers include innovative structural arrangement, improved structural efficiency, damage resistance, maintainability and repairability, and lower fabrication costs. Integrated design and Therm-X fabrication process to produce fuselage structure with frame/stringer intersections in a single cure operation.

MODELING AND DESIGN ANALYSIS METHODOLOGY FOR COMPOSITE PRIMARY STRUCTURE
NAS1-18754
1989 April - 1995 May

Project Engineer: Mr. O. F. Lopez
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3181 FTS 928-3181

Principal Investigator: Dr. L. W. Rehfield
Dept. of Mechanical Engineering
University of California
Davis, CA. 95616
(916)-752-0580

Objective: Develop and validate new structural models for aeroelastically tailored wings. Incorporate the non-classical deformation coupling modes of bending-transverse shear and extension-transverse shear into finite element structural analysis programs and account for section camber deformations in the analysis. Develop simple analytical models, useful for preliminary design and trade-off studies, that account for the essential physical behavior of the structure.

STUDY OF TAILORED COMPOSITE STRUCTURES OF ORDERED STAPLE THERMOPLASTIC MATERIALS
NAS1-18758
1989 April - 1995 May

Project Engineer: Ms. D. C. Jegley
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3185 FTS 928-3185

Principal Investigator: Dr. M. H. Santare
Dept. of Mechanical Engineering
University of Delaware
Newark, DE. 19716
(302)-451-2246

Objective: Develop and verify an analysis method to predict the response of curved beam structures that accounts for beams with various cross sections, microstructures, anisotropy and position-dependent material properties. Design curved beam test specimens made of ordered staple thermoplastic materials. Develop a methodology for fabrication of these test specimens that makes use of cost-effective manufacturing and sheet-forming technology.

ADVANCED TECHNOLOGY COMPOSITE AIRCRAFT STRUCTURES
NAS1-18889
1989 April - 1995 May

Project Engineer: Mr. W. T. Freeman
Mail Stop 241
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-2945 FTS 928-2945

Principal Investigator: Mr. P. J. Smith
Boeing Commercial Airplanes
M.S. 6N-21
P.O. Box 3707
Seattle, Wash. 98124
(206) 234-6733

Objective: To support NASA's goal to revitalize the nation's capacity for aeronautical innovation over the next decade by developing technology needed to apply composites to primary structures on commercial transport aircraft by the late 1990's. The technology shall provide a high level of technical confidence and demonstrate acceptable cost effectiveness for these specific objectives: (1) Develop basic technologies required to support cost effective damage tolerant pressurized fuselage structural designs and verify breakthrough technology results with mechanical tests. (2) Demonstrate advanced material placement processes and flexible automation for low cost assembly of pressurized transport fuselage structures. (3) Demonstrate the use of thermoplastic materials with advanced manufacturing techniques for fuselage clips, fittings, frames, and window belt reinforcements. (4) Develop the associated design, analysis and process technologies so that commercial application readiness and cost effectiveness can be realistically assessed. (5) Since the fuselage has the highest percentage of corrosion and fatigue problems on transport aircraft, composites will be evaluated for their potential to reduce repair and maintenance costs associated with airline life-cycle supportability. (6) Composite center fuselage elements will be eveloped because weight reductions at the airplane centerline are more effective in increasing payload, due to the offsetting dead-weight relief effects.

INNOVATIVE COMPOSITE AIRCRAFT PRIMARY STRUCTURES (ICAPS)
NAS1-18862
89 March 31 - 94 September 30

Project Engineer: Mr. Marvin B. Dow
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3090 FTS 928-3090

Principal Investigator: Mr. Raymond J. Palmer
McDonnell Douglas Corporation
Douglas Aircraft Company
3855 Lakewood Blvd.
Long Beach, CA 90846
(213) 593-7232

Objective: Develop and demonstrate innovative woven/stitched fiber preforms and resin matrix impregnation concepts for transport wing and fuselage structures. Demonstrate tow placement processes for transport fuselage structures. Demonstrate the use of thermoplastic materials with advanced manufacturing techniques for fighter aircraft fuselage structures.

NOVEL COMPOSITES FOR WING AND FUSELAGE APPLICATIONS
NAS1-18784
89 April 28 - 93 July 31

Project Engineer: Mr. H. Benson Dexter
Mail Stop 188B
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3094 FTS 928-3094

Principal Investigator: Mr. James Suarez
Grumman Aerospace Corporation
Aircraft Systems Division
South Oyster Bay Road
Bethpage, NY 11714-3582
(516) 346-3941

Objective: Integrate innovative design concepts with cost-effective fabrication processes to achieve damage tolerant structures that can perform at a design ultimate strain level of at least 6000 micro in./in. Integral structures will be fabricated using weaving and knitting/stitching concepts. Resin transfer molding will be used for low cost resin application and consolidation.

INNOVATIVE COMPOSITE FUSELAGE STRUCTURES
NAS1-18842
1989 April - 1995 May

Project Engineer: Mr. M. Rouse
Mail Stop 190
NASA Langley Research Center
Hampton, VA 23665-5225
(804) 864-3182 FTS 928-3182

Principal Investigator: Mr. R. B. Deo
M.S. 3853/82
Northrop Corporation
1 Northrup Ave
Hawthorne, CA. 90250-3277
(213)-332-2134

Objective: Develop innovative concepts for fighter aircraft fuselage structures that will improve structural efficiency while reducing manufacturing costs. Analysis methods and structural mechanics methodologies appropriate for the new structural concepts will also be developed and validated through tests of elements and components. Scaling laws that account for scale-up effects to predict the overall failure of built-up fuselage structure based on subscale tests will be developed. At least five design concepts will be selected and a detailed assessment made of their potential for meeting the program goals. Various matrix resins and material forms will be considered including toughened thermosets, thermoplastics, bismaleimides, polyimides, and polycrystalline materials in unidirectional and woven prepregs and woven, stitched, or braided preforms.Analysis techniques will be developed in three major areas: (1) structural details, (2) structural stability, and (3) scaling laws. Structural details to be considered include corner radii, lay-up discontinuities such as ply drop-offs and stiffener terminations, and stresses at cut-outs. Stability related analyses will be developed dealing with general instability, local-global buckling interactions, stiffener crippling, and stiffener/skin separation. Scale-up effects will be investigated through a building-block approach. Each structural detail will be analyzed i independently; then, analyses will be developed to predict probable failure sequences in large-scale built-up structure that account for load redistribution subsequent to first element failure.

WRIGHT RESEARCH AND DEVELOPMENT CENTER
MATERIALS LABORATORY

IN-HOUSE

ADVANCED COMPOSITES
WORK UNIT DIRECTIVE (WUD) NUMBER 45
88 October - 89 October

WUD Leader: James M. Whitney
Materials Laboratory
Wright Research and Development Center
WRDC/MLBM
Wright-Patterson AFB OH 45433-6533
(513) 255-9097, AUTOVON: 785-9097

Objective: The objective of the long term thrust is to develop understanding of deformation and failure process of composite laminates. The short term objectives include the following: (a) development of design methodology of thick composites and their test methods; (b) role of interface in emerging composite systems.

CONTRACTS

IMPROVED TECHNOLOGY FOR ADVANCED COMPOSITE MATERIALS
F33615-87-C-5239
15 Sep 87 - 1 Feb 92

Project Engineer: Marvin Knight
Materials Laboratory
Wright Research and Development Center
WRDC/MLBM
Wright-Patterson AFB OH 45433-6533
(513) 255-7131, AUTOVON: 785-7131

Principal Investigator: Rebecca C. Schiavone
University of Dayton Research Institute
300 College Park Avenue
Dayton OH 45469

Objective: The objective of this program is to investigate from both an experimental and an analytical standpoint the potential of new and/or modifications of existing matrix materials and reinforcements/product forms for use in advanced composite materials, including processing/mechanical property relationships. Such materials are subsequent candidates for use in advanced aircraft and aerospace structural applications.

MICROMECHANICS OF COMPOSITE FAILURE
F33615-88-C-5420
1 Oct 88 - 30 Sep 92

Project Engineer: Nicholas J. Pagano
Materials Laboratory
Wright Research and Development Center
WRDC/MLBM
Wright-Patterson AFB OH 45433-6533
(513) 255-6762, AUTOVON 785-6762

Principal Investigator: Som R. Soni
AdTech Systems Research Inc
1342 N. Fairfield Road
Dayton OH 45432

Objective: The objective of this program is to provide exploratory development in thermomechanical response, model material system development composite processing, and failure mechanisms investigations of composite and related constituent materials.

DEVELOPMENT OF ULTRA-LIGHTWEIGHT MATERIALS-N
F33615-88-C-5447
29 Apr 88 - 1 Jul 91

Project Engineer: James M. Whitney
Materials Laboratory
Wright Research and Development Center
WRDC/MLBM
Wright-Patterson AFB OH 45433-6533
(513) 255-9097, AUTOVON: 785-9097

Principal Investigator: Anne R. Beck
Northrop Corporation
Aircraft Division
One Northrop Avenue
Hawthorne CA 90250

Objective: To demonstrate the potential for advanced ultra-lightweight (ULW) materials and associated processes that will permit a fifty percent reduction in the structural weight of state-of-the-art (SOTA) high-performance aircraft that currently utilize up to ten percent of advanced composite materials in their structures.

DEVELOPMENT OF ULTRA-LIGHTWEIGHT MATERIALS-M
F33615-88-C-5452
13 May 88-15 Jul 91

Project Engineer: James M. Whitney
Materials Laboratory
Wright Research and Development Center
WRDC/MLBM
Wright-Patterson AFB OH 45433-6533
(513) 255-9097, AUTOVON: 785-9097

Principal Investigator: Gail L. Dolan
McDonnell Douglas Corporation
McDonnell Douglas Company
PO Box 516
St Louis MO 63166

Objective: To demonstrate the potential for advanced ultra-lightweight (ULW) materials and associated processes that will permit a fifty percent reduction in the structural weight of state-of-the-art (SOTA) high-performance aircraft that currently utilize up to ten percent of advanced composite materials in their structures.